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DESIGN AND CONSTRUCTION TECHNIQUES FOR SIFCON

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This report documents the first part of a three-part program to develop information and techniques necessary to consider SIFCON (Slurry Infiltrated Fiber Concrete) as a conventional building material. The report presents a discussion of preliminary design methods for flexure members followed by a summary of techniques for fabricating conventional-sized SIFCON structures. A section is included on the determination of material and fabrication costs for SIFCON. The report concludes with recommendations on how to use the information for implementing the second phase of the developmental program.

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TO METRIC (SI) UNITS OF MEASUREMENT

To convert from	To	Multiply by
degree (angle)	radian (rad)	1.745 329 E-02
degree Fahrenheit	kelvin (K)	$t_K = (t°_F + 459.67)/1.8$
foot	meter (m)	3.048 000* E-01
gallon (U.S. liquid)	meter^3 (m^3)	3.785 412 E-03
inch	meter (m)	2.540 000* E-02
kip (1000 lbf)	newton (N)	4.448 222 E+03
kip/inch^2 (ksi)	pascal (Pa)	6.894 757 E+06
ounce	kilogram (kg)	2.834 952 E-02
pound-force (lbf avoirdupois)	newton (N)	4.448 222 E+00
pound-force inch (lbf•in)	newton-meter (N•m)	1.129 848 E-01
pound-force/inch (lbf/in)	newton/meter (N/m)	1.751 268 E+02
pound-force/foot^2 (lbf/ft^2)	pascal (Pa)	4.788 026 E+01
pound-force/inch^2 (psi)	pascal (Pa)	6.894 757 E+03
pound-mass (lbm avoirdupois)	kilogram (kg)	4.535 924 E-01
pound-mass-foot^2 (lb•ft^2) (moment of inertia)	kilogram-meter^2 (kg•m^2)	4.214 011 E-02
pound-mass/foot^3 (lb/ft^3)	kilogram/meter^3 (kg/m^3)	1.601 846 E+01

1.0 INTRODUCTION

1.1 BACKGROUND

Since 1983 the New Mexico Engineering Research Institute (NMERI) has been conducting research and development work with SIFCON (Slurry-Infiltrated Fiber CONcrete) for the Air Force Weapons Laboratory (AFWL). One continuing program has been the development of a materials properties data base (Refs. 1, 2 and 3). Another program studied the used of SIFCON as a material for superhard missile silos (Refs. 4 and 5). More recently the work has centered on using SIFCON for hardened structures to resist ballistic and fragment perforation (Refs. 6 and 7). In addition to the work done for AFWL, NMERI has completed several projects for the New Mexico State Highway Department (NMSHD) using SIFCON as a paving material and to renovate bridge decks and beams (Refs. 8 and 9).

In the early projects, the SIFCON was fabricated in relatively small amounts using hand-mixing and hand placing techniques. In all of the work NMERI has done with SIFCON the fibers were placed by hand. Slurry placement advanced from pouring the slurry from the concrete mixer into buckets and thence into the fiber bed to pumping the slurry from a grout mixer. In the bridge deck and beam projects for the NMSHD, slurry was poured from buckets into the fiber bed. In the project testing SIFCON as a paving material, the slurry was poured from a ready-mix truck. In projects for AFWL, NMERI has either poured the slurry from buckets, for small test specimens, pumped slurry from a grout mixer into the top of the fiber bed, for revetments or slabs, or pumped slurry from a grout mixer into the bottom of the fiber bed, for a scaled silo. As the size and complexity of these projects increased, it became evident that large-scale fabrication techniques would need to be developed if SIFCON were ever to be considered a viable material for military or commercial construction.

In 1987 AFWL and NMERI prepared a comprehensive program to develop the information and techniques necessary to consider SIFCON as a conventional building material. This included developing appropriate fabricating techniques, quality control methods and structural design procedures. The first phase of this program was to research what construction methods existed

in the industry at the time and propose various techniques and equipment to design and fabricate full-size structural components with SIFCON. The second phase will be to construct, test and evaluate a variety of full-size SIFCON components using the proposed equipment and procedures developed in Phase I. The third phase will be to use the test data in combination with the material properties data base to verify and develop analytical structural design procedures for SIFCON. These design procedures will be presented in the form of a standard engineering design manual. The third phase will also include the development of standard quality control testing procedures for SIFCON.

1.2 SCOPE

This report documents the first phase of the SIFCON development program. Section 2.0 presents a discussion of a preliminary method for the design of flexure members with SIFCON. Section 3.0 reviews the techniques needed to fabricate conventional-sized SIFCON structures. A discussion on equipment currently available on the market suitable for use in fabricating SIFCON is included. Section 4.0 summarizes a study to determine the various material and labor costs associated with SIFCON construction. The section includes the design of a conventional concrete flexure member and several examples of redesigned structural systems using SIFCON. In support of the cost analysis, a summary of the results of a program (Ref. 3) to study the effects of including sand in the slurry are included. The report concludes with several recommendations on how to use the information for implementing the second phase of the developmental program.

2.0 STRUCTURAL DESIGN WITH SIFCON

2.1 INTRODUCTION

A comprehensive discussion of textbook-type design methods for SIFCON is premature at this stage in the development of SIFCON. However, some preliminary work has been done at NMERI, particularly in design methods for flexure members.

2.2 ELASTIC METHODS

Within certain limits, it is believed that SIFCON can be designed using the classic elastic methods and formulas. These limits are defined as the initial linear portion of the SIFCON stress-strain curve, up to the proportional limit, as reported in Reference 1. For stresses less than this value, classic formulas apply. For example, the flexure formula: $f=Mc/I$, where M is the bending moment, I is the area moment of inertia of the section, c is the distance from the neutral axis and f is the calculated stress at that point, is applicable as long as the stress, f, remains below the proportional limit. Examples of flexure members with SIFCON, designed using elastic methods, are presented in Section 5.0.

2.3 STRENGTH METHODS

For many conventional designs using well-defined static-type loads, the constraint of elastic methods poses little problem. However, for structures subjected to dynamic or impact-type loads, such constraints severely limit SIFCON's full potential. For these cases, a "strength" method of design is needed. This is the currently accepted design method for conventional reinforced concrete in the United States and Europe. For the strength method to be meaningful, well-defined stress-strain relationships for the material are needed.

2.3.1 Stress-strain Relationship

For conventional reinforced concrete strength design, an assumption is made concerning the stress-strain relationship of the concrete in compression. The assumption states that the concrete "fails" at a strain of 0.003 and at that time the stress is distributed as shown in Figure 1. In addition, the assumption states that at the time the concrete reaches the maximum strain, the stress in the reinforcing steel is determined according to the stress-strain relationship shown in Figure 2. Given a cross section of a flexural member and these assumptions, the only unknown

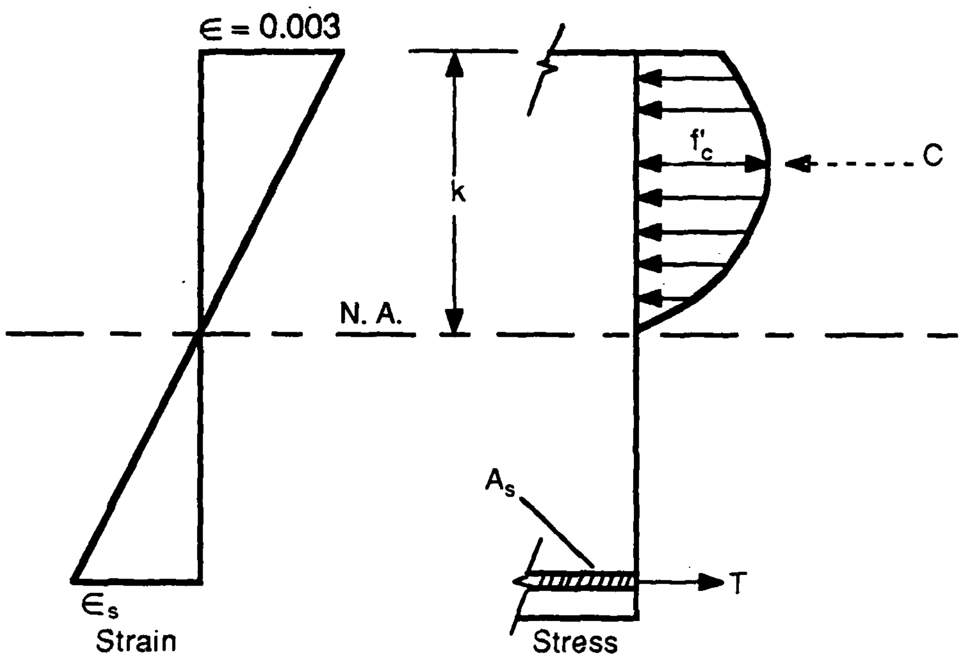


Figure 1. Strain and stress distributions for the design of a conventional concrete flexure member.

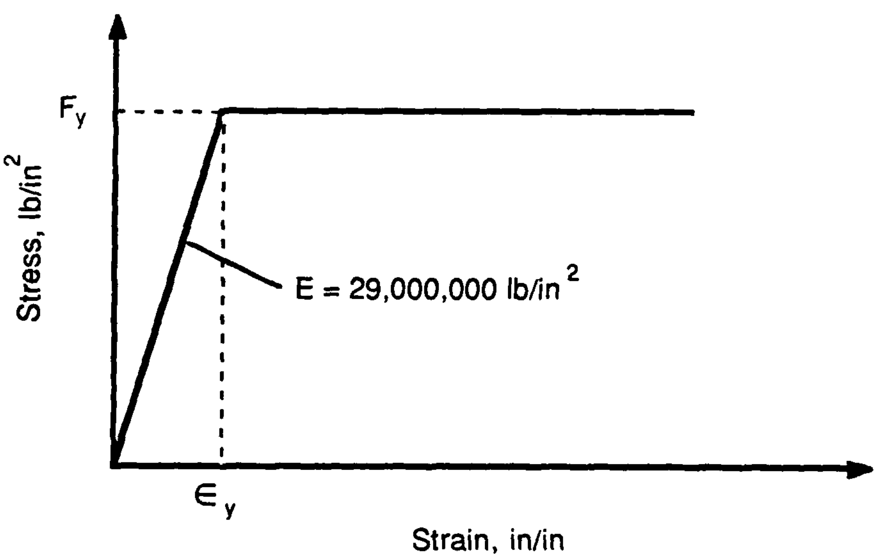


Figure 2. Stress-strain diagram for reinforcing steel.

is the location of the neutral axis, dimension k (Fig. 1). Using the basic principles statics and strength of materials, the location is determined from which the bending moment capacity of the member can be calculated.

The same philosophy can be used for SIFCON. A typical stress-strain diagram is shown in Figure 3 (from Ref. 1). Some of the points of interest are the stress at the proportional limit of 9,600 lb/in^2 with a strain of 0.0085 (point A). The Modulus of Elasticity in this linear region calculates to 1,129,400 lb/in^2. The curve then has a nonlinear transition from point A to B. Next is a second linear portion from point B to C, with a slope of 94,400 lb/in^2. The curve finally has a nonlinear transition to the ultimate stress of 18,000 lb/in^2 at a strain of 0.050 (point D).

From the stress-strain relationship, the assumption would state that the SIFCON "fails" at a strain of 0.050. From this, a strain diagram and stress distribution can be drawn for the section (Fig. 4). Adding the assumption that the reinforcing steel has yielded according to the same diagram used for concrete (Fig. 2), the location of the neutral axis can be calculated. Both the area of the stress diagram and its centroid must be calculated, however, so the stress diagram must be described mathematically in order to perform an integration. This is not conducive for efficient engineering design procedures, and was the same problem encountered when the strength design methods were being developed for reinforced concrete. To simplify the design process for conventional concrete, an equivalent rectangular stress-strain diagram was used. The width and height of the rectangle were adjusted to give a design capacity comparable to empirical test results.

Following this procedure for SIFCON, an equivalent stress-strain diagram could be assumed as shown in Figure 5. The maximum stress value would be set at some percentage of the ultimate stress. For this diagram, a value of 80 percent was arbitrarily selected, resulting in a maximum stress of 14,400 lb/in^2. Because the modulus of elasticity of SIFCON is about one-third that of conventional concrete, the equivalent stress-strain diagram was made to follow the initial slope of the SIFCON diagram to the intersection with the maximum stress value of 14,400 lb/in^2 and a calculated strain of 0.013.

Using the strain diagram and the simplified equivalent stress distribution, some general equations can be developed for calculating the location of the neutral axis and eventually the capacity of the member (Fig. 6). For a width, b, the following equations can be written:

$$C_1 = F_c\,(k_1)\,b \qquad (1)$$

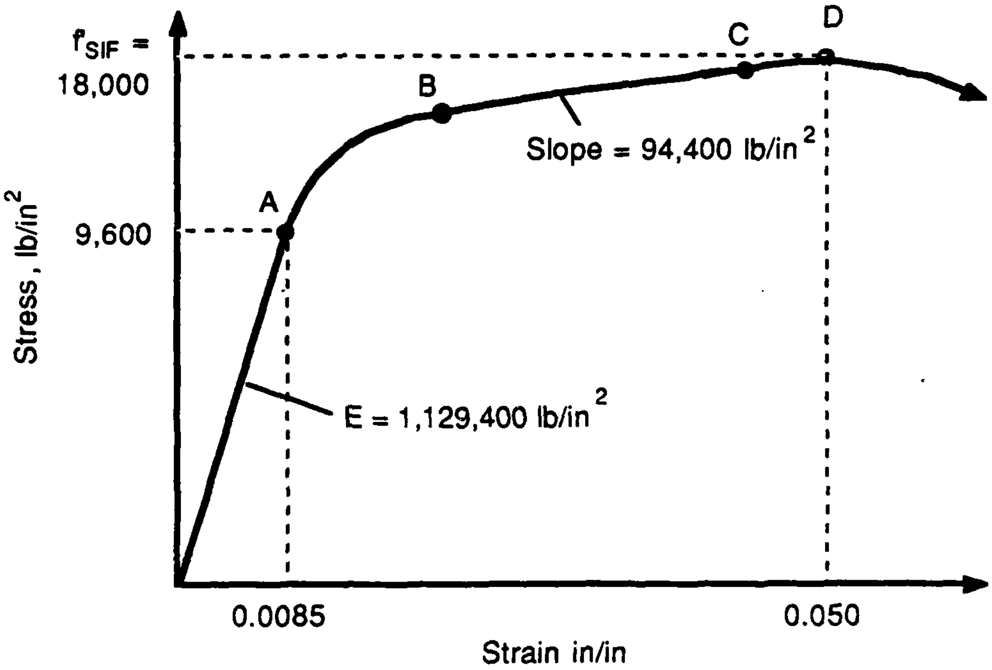


Figure 3. Typical SIFCON stress-strain diagram (from Ref. 1).

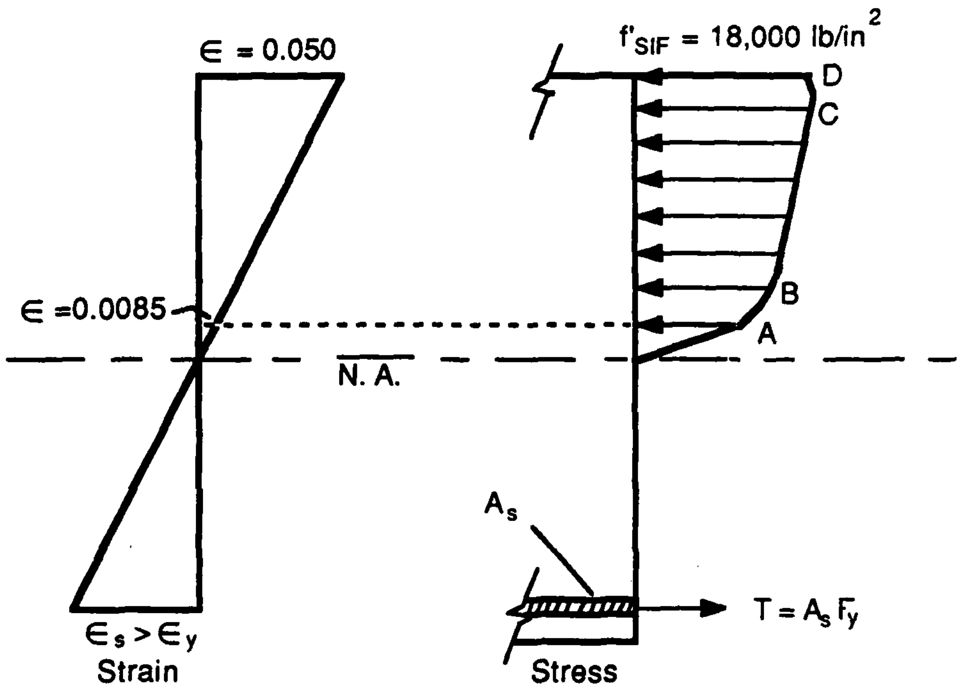


Figure 4. Stress and strain distribution for the design of a SIFCON flexure member.

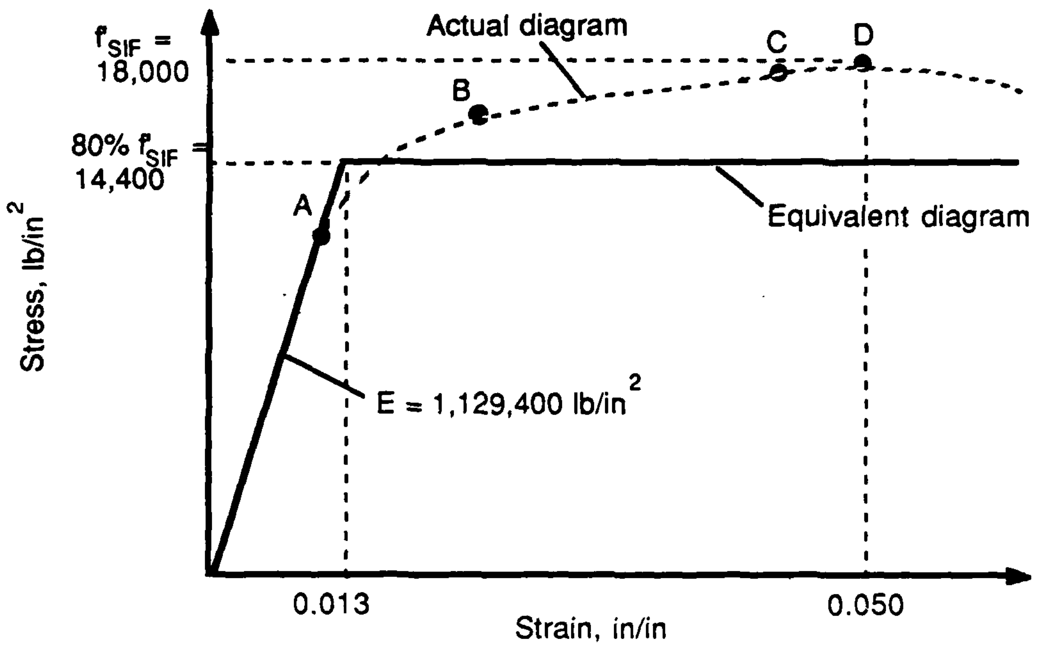


Figure 5. Equivalent stress-strain diagram for designing SIFCON flexure members.

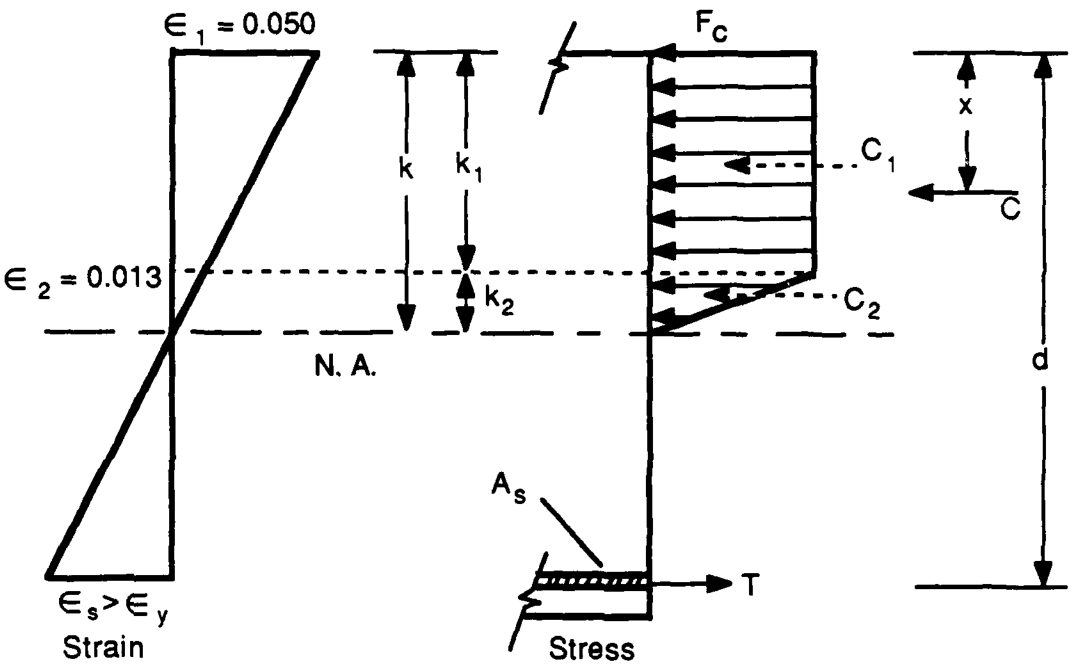


Figure 6. Strain and equivalent stress diagrams for designing a SIFCON flexure member.

$$C_2 = F_c\,(k_2/2)\,b \tag{2}$$

The total compression component is the sum of these two equations:

$$C = C_1 + C_2 \tag{3}$$

or

$$C = F_c\,(k_1 + k_2/2)\,b \tag{4}$$

For the tensile component (assuming $\varepsilon_s > \varepsilon_y$):

$$T = A_sF_y \tag{5}$$

Equating the two:

$$T = C\,;\;\; A_sF_y = F_c\,(k_1 + k_2/2)\,b \tag{6}$$

From the strain diagram, the relationship of k_1 and k_2 to the depth k and the specified strains ε_1 and ε_2 can be determined by proportion and substituted into the equation:

$$A_sF_y = F_c\,(k)\,(1 - \varepsilon_2/(2\varepsilon_1))\,b \tag{7}$$

Rewriting the equation to solve for k:

$$k = (A_sF_y)/(F_c\,(1 - \varepsilon_2/(2\varepsilon_1))\,b) \tag{8}$$

With k known, k_1 and k_2 can be calculated and the centroid of the compression component can be determined:

$$x = (k_1k_1 + k_1k_2 + k_2k_2/3)\,/\,(2k_1 + k_2) \tag{9}$$

The moment capacity can then be calculated as follows:

$$M = A_sF_y\,(d - x) \tag{10}$$

For typical SIFCON stress-strain curves, k_1 is approximately 75 percent of k, and k_2 is, therefore, 25 percent of k. In addition, assume F_c is defined as 80 percent of the ultimate SIFCON strength, F_u. With these conditions and assumptions, the equation can be simplified and presented in a form similar to the equations used in conventional concrete design. Equation 6 becomes:

$$A_sF_y = .80F_u\,0.875kb \tag{11}$$

Equation 8 simplifies to:

$$k = (A_sF_y)/(F_u\,0.70b) \tag{12}$$

Solving for x in Equation 9 reduces to:

$$x = 0.4405k \tag{13}$$

and the moment capacity equation is:

$$M = A_sF_y\,(d - 0.44k) \tag{14}$$

Such simple equations can be deceiving because of the assumption that the reinforcing steel has yielded. For conventional concrete design this is usually not a problem, as most of the design codes limit the percentage of reinforcing to ensure yielding of the steel. Because of the high strain SIFCON experiences at its ultimate strength, care must be exercised in making sure the associated reinforcing steel is not ruptured. This is illustrated in the following example:

Given: $b = 12$ in
$d = 24$ in
$A_s = 3.0\ \text{in}^2$ $(p = 0.0104)$
$F_y = 60{,}000\ \text{lb/in}^2$
$F_u = 15{,}000\ \text{lb/in}^2$

The following parameters are calculated using the formulas developed above:

$k = 1.43$ in
$M = 4{,}207{,}000$ in-lb

Using a maximum strain of 0.050 in the SIFCON, the strain at the level of the reinforcing steel calculates to be 0.790. This is nearly 400 times the yield strain of the steel (0.002), and it can be assumed the steel would rupture well before the calculated strength of the member had been achieved. As a point of interest, a flexural member of the same dimensions and reinforcing, using a 5,000 lb/in^2 conventional concrete would have a calculated strength of 3,982,500 in-lb.

This example points out that, to make use of the full potential of SIFCON's strength and toughness, a much larger percentage of reinforcing steel must be used for members with SIFCON than for conventional concrete.

This is illustrated by reworking the example with $A_s = 12$ in^2. The following parameters are calculated:

$$k = 5.71 \text{ in}$$
$$M = 15{,}471{,}000 \text{ in-lb}$$

The strain at the level of the reinforcement was calculated to be 0.160. Although this is much less than the value from the first example, it is still more than 70 times the strain for yielding of the steel. In addition, the percentage of reinforcing is now about 4 percent, which is about twice the percentage usually permitted by code for conventional concrete design. However, the moment capacity is three times larger than for the first example. But to make full use of both the steel and the SIFCON, still more reinforcing is required.

Reworking the example with $A_s = 30.0$ in^2:

$$k = 14.29 \text{ in}$$
$$M = 31{,}882{,}000 \text{ in-lb}$$

The strain at the level of the reinforcement was calculated to be 0.034. This value is in the range of strains found in conventional reinforced concrete design. The calculated moment capacity of the SIFCON member is about 8 times larger than for the same sized member using concrete, but it required 10 times the amount of reinforcing steel to achieve that capacity.

Assuming the reinforcing bars could be physically placed in the member, and using the cost indices developed later in this report, the cost of the SIFCON system was found to be about 15 percent

less than a concrete system with an equivalent capacity. The equivalent concrete system used for this comparison had a strength of 5000 lb/in^2, used the maximum reinforcing steel permitted by code and had a depth 75 percent greater than the SIFCON system. When compared to a second equivalent concrete system having the same parameters as the first but a depth of 50 percent greater than the SIFCON system, it was found the SIFCON beam cost 25 percent less. A final comparison considered an equivalent concrete beam with a reinforcement ratio about half of the maximum amount allowed by code, which is more typical of well proportioned concrete beams. For this case the concrete beam required a depth nearly 2.5 times greater than the SIFCON beam, and cost 65 percent more.

This design method for flexure members with SIFCON appears to produce a member with a significantly larger strength than for a concrete member of the same depth. In addition, the cost of the SIFCON system appears to be quite competitive with an equivalent concrete system. However, using this design method, the SIFCON system requires a relatively high percentage of reinforcing steel to make use of the full potential of the SIFCON.

As noted in the previous examples, a member using SIFCON can be designed with a smaller depth than a concrete system of the same capacity. This is illustrated by reworking the first example with twice the amount of steel and about half the depth, $A_s = 6\ in^2$ and $d = 12.5$ in. The following parameters were calculated:

$$k = 2.86 \text{ in}$$
$$M = 4{,}047{,}000 \text{ in-lb}$$

Using similar comparison techniques as describe above, it was found that the cost for the SIFCON system was about 25 percent less than a typical equivalent capacity concrete beam. In addition, the percentage of reinforcing steel was a more reasonable amount ($p = 0.208$). The strain at the level of the reinforcing steel was calculated to be 0.169. Although this is higher than typical values for concrete, it may still be within the range of the material's capacity.

2.3.2 Summary

There are two areas of interest in flexure members using SIFCON that are designed with the previously described strength methods. The first area concerns the generally large amount of reinforcing steel needed. Because of the great strength and toughness of the SIFCON, more steel is needed to take advantage of the material's full potential. At this time, not much can be done to

improve the situation because of the limits imposed by the reinforcing bars that are commercially available. However, consideration could be given to encouraging the development of deformed bars of higher yield stress. Historically, this was the path followed by the concrete industry. As the "typical" concrete strength increased from 3000 lb/in^2 to 4000 lb/in^2 and higher, the strength of the reinforcement increased from 40,000 lb/in^2 to 60,000 lb/in^2. Another solution is the use of conventional prestressing strands with strengths up to 250,000 lb/in^2 instead of conventional deformed reinforcing bars.

A second concern is the smaller depths needed for members using SIFCON. Although the calculated strains are within the defined limits, the member may not be stiff enough, resulting in deflections larger than acceptable. This condition may be resolved by using sections that are deeper and narrower than traditional reinforced concrete member proportions.

In summary, flexure members using SIFCON can be designed by strength methods using the procedures and equations described in this section. The reader is cautioned that the formulas are preliminary and must eventually be verified by testing before they can be considered accurate and useful for the design engineer. Until further development and verification, structural designs should be limited to elastic methods.

3.0 SIFCON CONSTRUCTION TECHNIQUES

3.1 INTRODUCTION

There are five basic elements to consider when fabricating SIFCON: (1) formwork, (2) fiber placement, (3) slurry placement, (4) finishing and (5) curing. The selection of the fiber type and the slurry mix design are considered to be functions of the design process and beyond the scope of this section. The following discussion will assume that the fiber type and slurry have already been determined.

3.2 FORMWORK

The formwork for SIFCON is similar to that for conventional concrete. Both steel and wood forms have been successfully used in the past. The design of the form follows the same procedures for concrete using the hydrostatic pressure from the slurry. The formwork design procedures developed by the American Concrete Institute (ACI) attempt to consider the fact that concrete attains some internal strength due to the bridging effect of the aggregate in the concrete and the result of the initial setting of the cement during the time of placement. Therefore, the pressure distribution on the form work is not necessarily hydrostatic from top to bottom, but is limited to a maximum pressure dependent on the rate of placement, temperature and consolidation techniques.

For forms designed for SIFCON, the same procedures may be applied. The fluid densities of SIFCON slurries are generally less than conventional concrete and have been measured in the range of 125 to 145 lb/ft^3 (Refs. 1 and 2). Only limited data are available on the relationship of slurry "open time" versus some of the slurry design parameters such as water-to-cement ratio. No data are available for SIFCON on the relationship of initial set of the slurry versus temperature. These relationships will have to be identified in order to establish accurate pressure distributions expected on SIFCON formwork.

Despite the lack of these data, it is felt that the forms for SIFCON structures can still be designed--although somewhat conservatively. Because of the slurry placement procedures used for SIFCON, the slurry is usually designed to remain "open," or in a fluid state, for a relatively long time. This is necessary to allow the slurry to flow through and fully infiltrate the fiber bed. In addition, most typical structural components are relatively short, say, 10 ft or less in height, and could probably be filled in less time than needed for the slurry to begin its initial set. Therefore,

using a full hydrostatic pressure distribution for the designing of the forms is not an unreasonable assumption.

As an example, using the ACI procedures, a 10-ft-high wall, with the concrete placed at a rate of 10 ft /h and a temperature of 60 °F, requires the form to be designed for a maximum pressure of 1340 lb/ft^2. The same formwork for a SIFCON wall should be designed for a maximum pressure of 1450 lb/ft^2, or a pressure 8 percent larger than for concrete.

Consider another example using a 5-ft-high wall and the same placing and temperature conditions noted in the first example. The maximum pressure required for conventional concrete using the ACI procedures would be 900 lb/ft^2. However, the same wall with SIFCON requires a design pressure of only 725 lb/ft^2 or 20 percent less than for the concrete wall.

Forms for SIFCON can be assembled in the same manner as for conventional concrete. However, more care should be taken to ensure the forms and joints are watertight to prevent the slurry from leaking. Caulking the joints and holes during assembly has proven effective in sealing the forms.

Since SIFCON requires watertight forms, consideration should be given to providing a drain system in any formwork exposed to the elements. This will allow any rain or runoff water entering the formwork to be removed prior to placing the slurry. Openings in the bottom of the forms (which are sealed just prior to placing the slurry) such as petcocks or hose bibs, are examples of simple form drainage systems. If a drainage system is impractical, consideration should be given to providing alternate weather protection such as tarps or tents over the forms.

Formwork for walls or columns should be designed for the use of external form vibration. This is especially necessary if the slurry is designed to be poured into the fibers from the top of the form. Generally, small pneumatic vibrators of the type used on bulk cement hoppers, spaced about 6 ft on centers on one side of the form, have been shown to be adequate for walls up to 8 in thick. For thicker walls, small vibrators on both sides of the wall or larger external form vibrators could be used.

As for concrete construction, all exposed corners on SIFCON components should be chamfered 0.5 to 0.75 in. Fabricating thin ribs, extensions, or acute corners, which must remain undamaged during the removal of the forms, is generally more successful with SIFCON than with conventional concrete. However, care should be taken to provide reasonable chamfers at sharp corners. Formwork for rustication grooves, insets and blockouts should be provided with

adequate draft to facilitate removal of the forms. For components requiring stepbacks or ledges, the formwork should be designed to permit complete fiber placement under the formwork. In general, the horizontal part of the form should be designed to be installed after the fiber has been placed. Small holes in the horizontal formwork should be provided to allow any air trapped under the ledge to escape as the slurry rises in the form. After the slurry reaches the level of the holes and begins to flow out, the holes can be sealed with plugs or screws. The use of architectural form liners can also be used with SIFCON.

Embedded items such as threaded inserts, plates, and pipe sleeves can be installed in SIFCON formwork using the same techniques as for conventional concrete. Care should be taken to ensure that any fasteners penetrating the form to support the embedded items are adequately sealed to prevent leakage of the slurry.

3.3 FIBER PLACEMENT

The major consideration for placing the steel fibers in the form is that they must be allowed to fall freely as individual fibers into the form. This procedure allows the fibers to interlock forming a continuous uniform mass. If the fibers are placed in clumps, they do not interlock and lines of weakness will be formed in the SIFCON (Fig. 7).

In the past, the fiber placement for SIFCON has been done by hand. A handful of fiber was taken from the container and sprinkled into the form. The placement rate using the hand method was in the range of about 4 to 10 lb/min. While this method and rate was suitable for the small components needed at the time, it is probably quite inefficient for fabricating full-size structural components. For such structures, a mechanized or automated system will be necessary if any economy is to be realized.

A review of several fiber and equipment manufacturers across the country has indicated that there are equipment and systems available today that can be directly employed or economically adapted for placing the steel fiber in SIFCON. In general, all the fiber placement equipment reviewed and observed can be classified as having two basic parts. The first part is a system that takes the mass of interlocked fibers--as it comes packaged from the manufacturer--and separates it into single individual fibers. The second part is a transportation system that moves the fiber from the first system to a location where it can fall freely into the form. A brief description follows of several different systems available today.

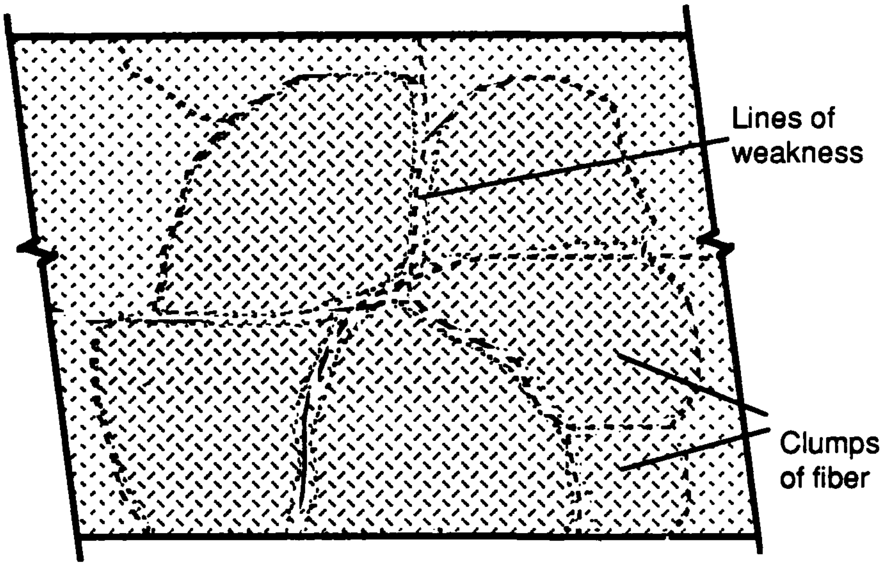


Figure 7. Lines of weakness from fibers placed in clumps.

3.3.1 Rotating Drum

The rotating-drum system consists of a cylindrical or slightly conical steel drum (Fig. 8). The drum is mounted with its longitudinal axis ranging from about 45 deg to nearly horizontal. A circular steel plate is mounted at the lower end of the drum. A gap, ranging from 10 to 30 mm (0.375 to 1.25 in) in width, is provided between the edge of the plate and the wall of the drum. Inside the drum, a series of short steel rods or studs are welded to the wall. The upper end of the drum is open.

In operation, a mass of interlocked fiber, as it comes packaged from the manufacturer, is dumped into the open end of the drum. The drum is then rotated by a motor at about 1 to 2 r/s. As the drum turns, the steel rods catch the fiber mass and carry it around to the top where it falls back to the bottom. This movement keeps the large fiber mass away from the end plate and at the same time breaks up the fiber mass into individual fibers as it falls. The individual fibers slide down the wall of the drum, through the gap between the end plate and the wall, and fall off the end of the drum. The fibers fall onto a transport system such as a conveyor belt or vibrating tray where they are carried to the form. The system could be used to place fibers for thin SIFCON slabs or pavements without a transportation system by moving the entire drum system back and forth over the area until the correct thickness of fiber is achieved.

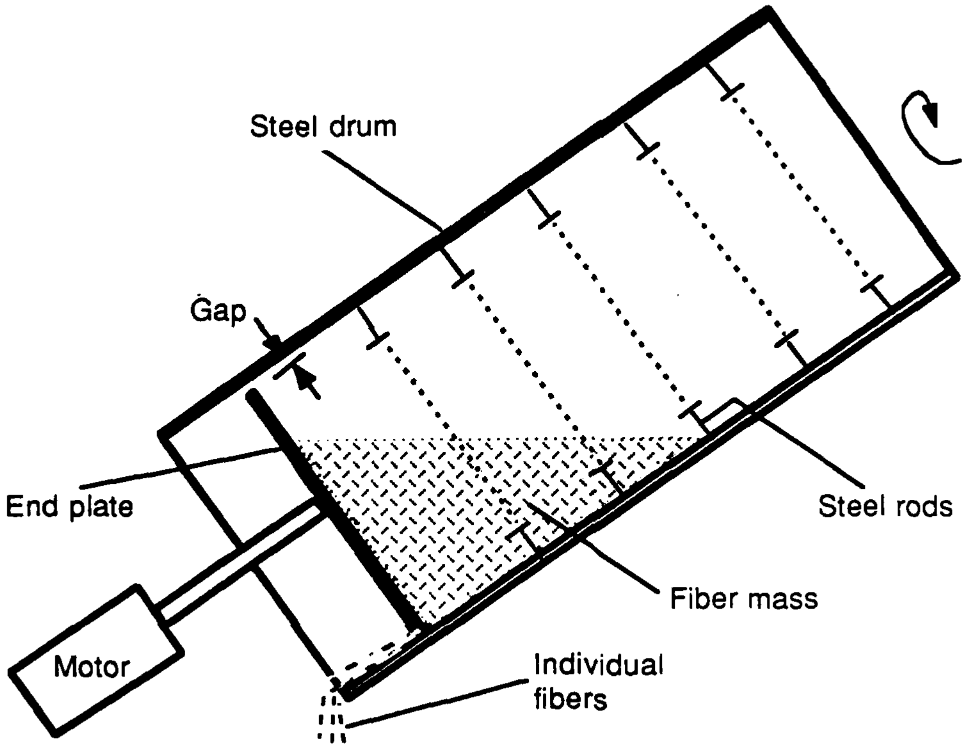


Figure 8. Fiber distribution system with rotating drum.

A version of the rotating drum system is one where the drum is stationary and the end plate rotates (Fig. 9). Steel rods or studs on the rotating end plate break up the fiber mass into individual fibers which fall out between the plate and the drum wall as before.

Examples of each of the two versions are in operation today for adding fiber to a conventional concrete mix being prepared in a standard transit-mix truck. Both systems are relatively simple in design and are probably fairly inexpensive to fabricate. In addition, they are probably inexpensive to operate since operation requires only one or two semiskilled or unskilled laborers.

Because the systems observed are designed for use in making conventional fiber-reinforced concrete with a fiber volume density of 2 percent or less, their maximum fiber-output rate is about 45 to 65 lb/min. Redesigning the system by increasing the diameter of the drum, the geometry of the steel rods and/or the speed of rotation may help to increase the fiber-output rate.

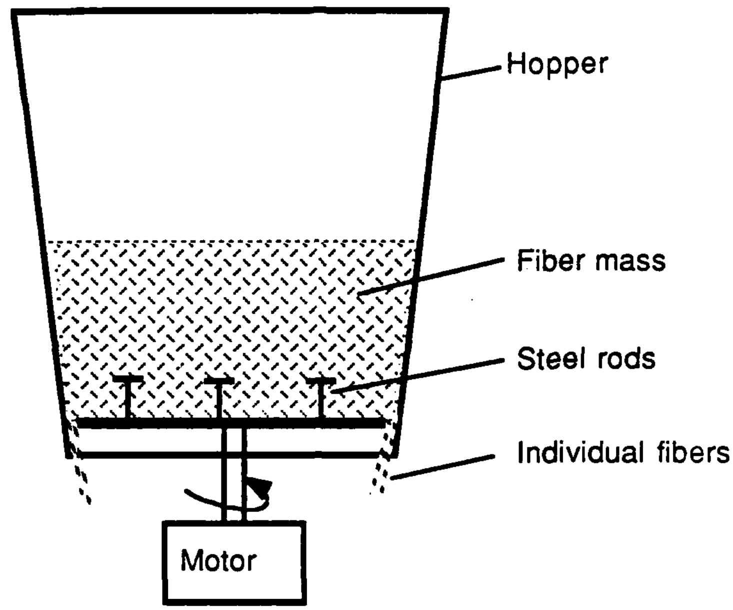


Figure 9. Fiber distribution system with rotating plate.

3.3.2 Vibrating Screens

The vibrating screen system consists of a circular or rectangular steel hopper. Inside the hopper are one or more levels of screens. The openings in each sucessive layer of screens vary from large to small with the largest openings in the uppermost screen (Fig. 10).

In operation, a mass of fibers, as it comes from the manufacturer, is dumped into the top of the hopper, where it comes to rest on the top screen. The hopper system is then rapidly shaken or vibrated. This vibration causes smaller clumps of fibers to fall through the upper screen onto the lower one. Smaller and smaller clumps of fiber continue to fall through the openings in the successively lower screens until only individual fibers fall from the last screen. The individual fibers fall out of the bottom of the hopper onto a transportation system such as a conveyor belt or vibrating tray which carries them to the form.

Vibrating screens and trays are common in the manufacturing industry today. For example, a system similar to the one described above is used to separate and package nails and bolts. Discussions with manufacturers of vibratory equipment indicate that almost any type of system can be designed and built to meet the needs of the user. The hopper system described is simple to fabricate and operate, requiring only off-the-shelf equipment. As with the rotating drum system, the vibrating system can be operated with only one or two unskilled laborers.

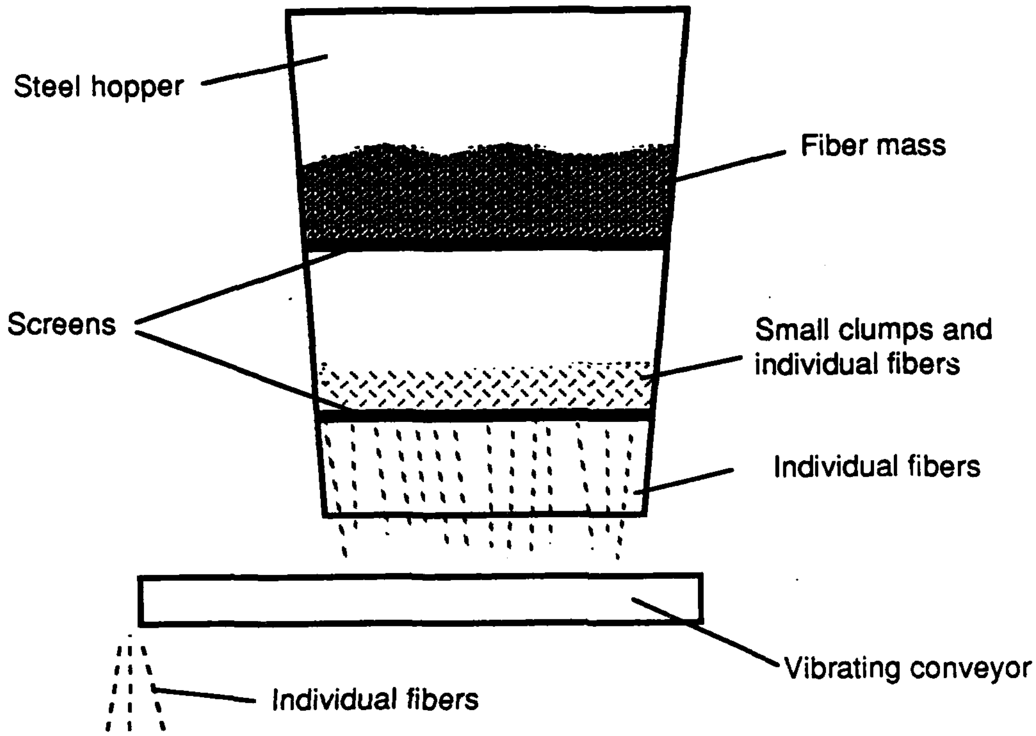


Figure 10. Fiber distribution system with vibrating screens.

One manufacturer of vibrating screens provided a simple demonstration of the capabilities of one of several systems of vibrating screens suitable for fiber placement. The particular equipment produced a fiber output rate of about 200 lb/min, or about 4 times higher than the output rate for the rotating drum system. At this rate, a panel 4 ft by 8.5 ft by 6 in thick could be filled in about 4 min with a fiber having a volume density of 10 percent. By comparison, it would require one man more than 1 hr to fill it by hand.

3.3.3 Pneumatic System

A demonstration of a system incorporating standard pneumatic concrete equipment common to the shotcrete industry to separate and distribute the fiber was observed. For this system, the mass of fibers are placed into the cylindrical hopper normally used for the concrete material. In operation, a small clump of the fiber would be mechanically separated from the main fiber mass by the equipment and eventually end up at the entrance of a 3-in-diam rubber hose. In the hose, a high-velocity stream of compressed air would break up the small clump and carry the individual fibers down the hose to the other end where they would be blown into the form.

The system did not work well. The fibers continually jammed the hopper mechanism and the compressed air was generally ineffective in moving the fibers down the hose in any sizable output rate. The system as it presently exists would be of marginal use for SIFCON fiber placement. With some modifications to the system, its potential for effective use in SIFCON may be good.

3.3.4 Other Systems

Another fiber distribution system, currently in use by a manufacturer of security vaults, was observed. Because the device is a prototype design and considered proprietary by the owner, no major details can be reported here. However, the fiber-output rate for this machine is in the range of 400 lb/m, or twice the rate for the particular vibrating screen system noted above. This system uses standard off-the-shelf materials and equipment, can be operated by one person and is easily adjusted to produce a broad range of fiber output rates. The owner expressed an interest in either selling, leasing, or licensing the use of the equipment.

3.4 SLURRY PLACEMENT

The major consideration for placing SIFCON slurry is to ensure that all the ingredients are thoroughly mixed and contain no lumps of cement or fly ash. Such lumps have a tendency to block the openings in the fiber bed and restrict the infiltration of the slurry. In the past, slurry mixing has been done in small, impeller-type mortar mixers. The slurry was then transferred to a bucket and carried to the form where it was poured into the fiber bed. While this method was suitable for building the small components and test specimens needed at the time, it would be an inefficient method for fabricating full-size SIFCON structures.

A review of the industry has indicated that there is a variety of standard common equipment in use today which can be readily employed for mixing and placing the SIFCON slurry. As with the placement of the steel fibers--the equipment for placing the slurry can be divided into two main components: (1) a system to mix the ingredients, and (2) a system to transfer the slurry to the form and infiltrate it through the fiber bed. A brief description of some systems currently available for slurry placement follows.

3.4.1 Grout Mixers

A standard grout mixer is ideal for mixing the SIFCON slurry. It includes a hopper or tub for mixing the ingredients, and usually has a metering system to accurately measure the water. Impeller blades or paddles rotate through the slurry to ensure proper mixing and help to break up any lumps. Most grout mixers are manufactured in combination with a grout pump and hose to transfer the slurry to the form. The pump allows the slurry to be discharged into either the top of the fiber bed (Fig. 11), or the bottom (Fig. 12).

Grout mixers and pump systems are available in a variety of sizes and capacities from a number of different manufacturers. The slurry output rates can range from 2 to 20 ft^3/min with pressures up to 250 lb/in^2. Most mixers are designed for use with premixed grouts packaged in standard size bags. For efficient use of these grout mixers, a SIFCON slurry would need to be designed using proportions based on full standard bags of cement and fly ash rather than in bulk form. This procedure also requires two operators to open the bags and fill the hopper on a continuous basis.

There is at least one company which manufacturers several sizes of large self-contained grout mixing systems which utilize automatic, continuous batching procedures. In the largest system, the dry ingredients are located in large hoppers mounted on a 50-ft truck trailer (Fig. 13), and are continuously fed by an auger into a large grout mixer where the liquid is added. The mixed slurry flows into a conventional grout pump system which delivers the grout through hoses to the fiber bed. The system has the capability to make an infinite range of mixes of varying proportions. It can produce slurry at fast or slow rates depending on the specific requirements. The quantity output of the system is limited only by the size of the hoppers. Currently, the capacity of the system is rated at 16 yd^3. However, the hoppers can be easily recharged at the work site using bulk transport trucks or at a central facility. The system is fairly efficient to operate, requiring only one or two people. The cost for the system is about \$125,000 to \$150,000 depending on the type of equipment needed. A smaller version of the system with a capacity of 6 yd^3 is also available at a cost of \$35,000 to \$40,000 (1987 prices).

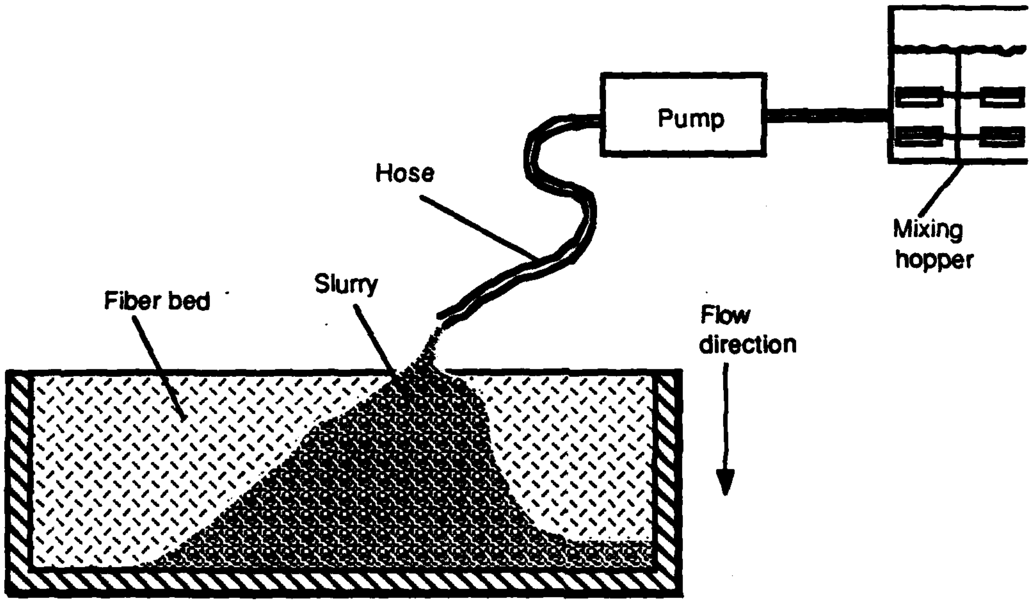


Figure 11. Infiltrating slurry from the top of a shallow fiber bed.

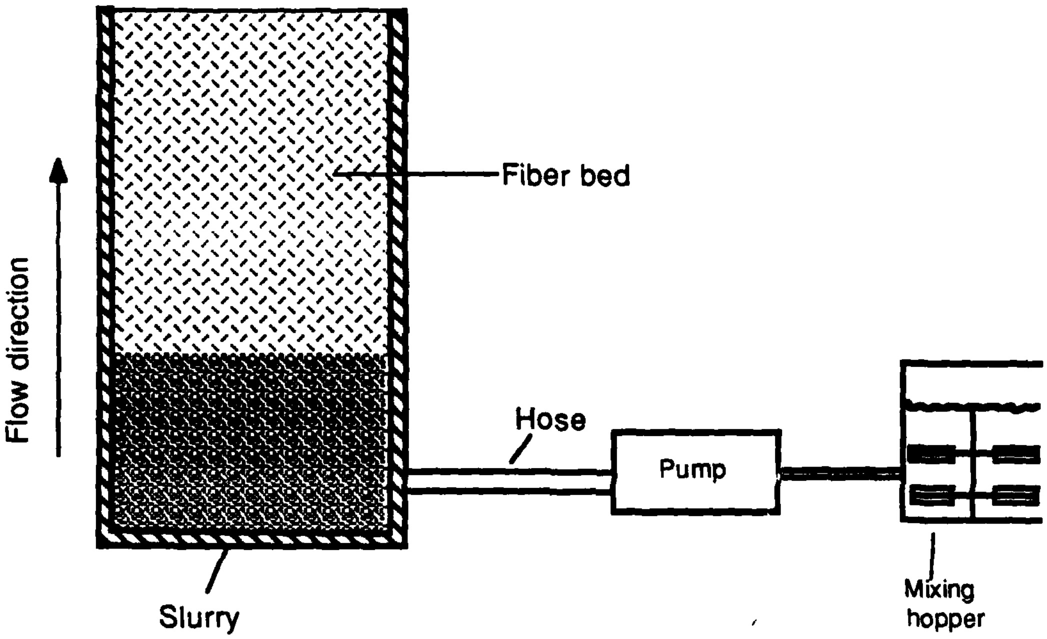
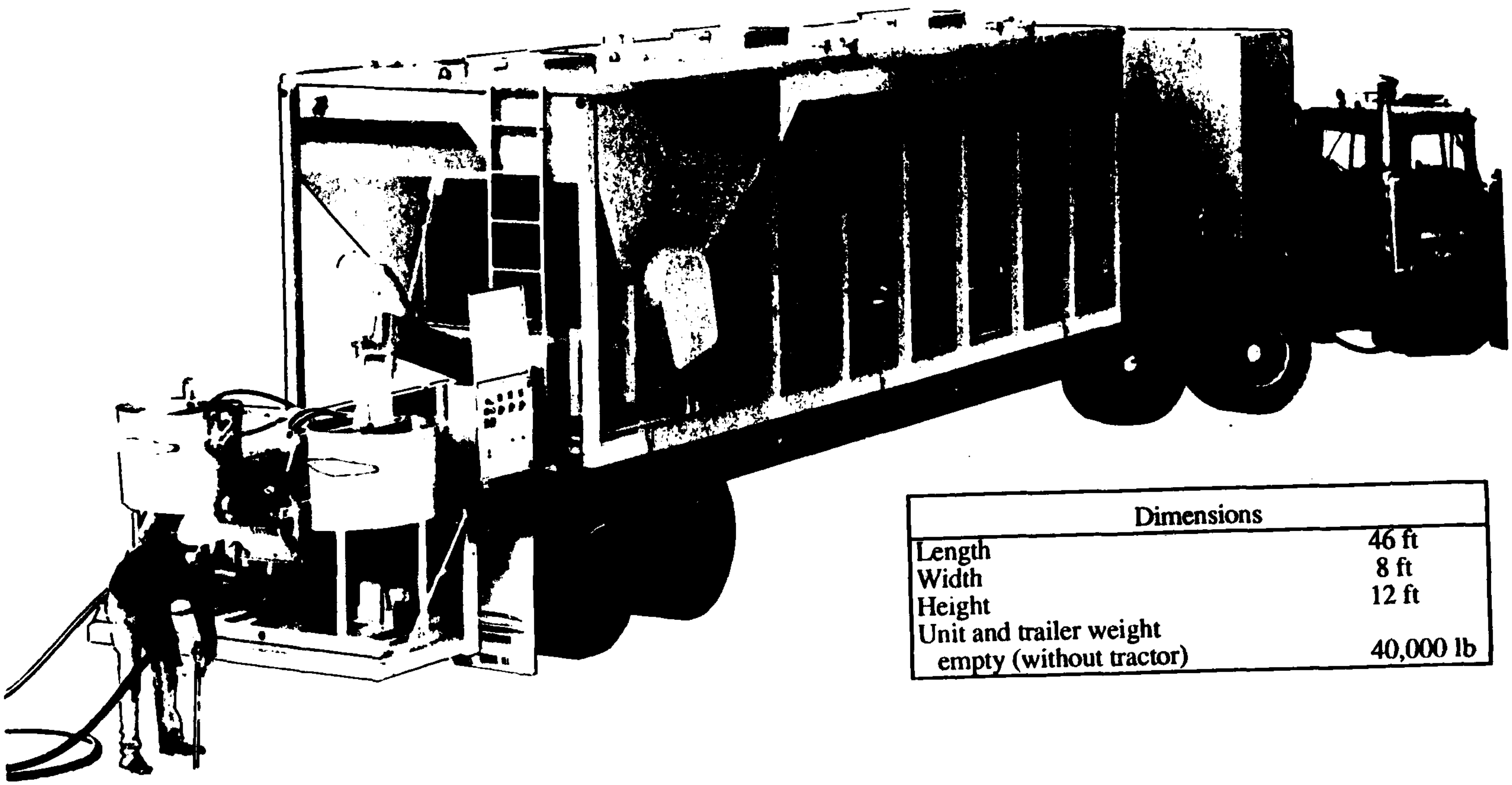


Figure 12. Pumping slurry into the fiber bed from the bottom to the top.

Automated, electronic central control panel
for one-man operation

Accurately meters materials for required mix ratios

Transports, mixes, and pumps up to 16 yd^3 of bulk materials--cement/fly ash (cement/sand bulk material transport optional)



Dimensions	
Length	46 ft
Width	8 ft
Height	12 ft
Unit and trailer weight empty (without tractor)	40,000 lb

Figure 13. Slurry Mixing Trailer.

3.4.2 Transit Mix Trucks

Because of their widespread use, transit-mix concrete trucks are also ideal for mixing SIFCON slurry. They can be used without modification, and require only one driver/operator. They are associated with the concrete industry, and operate out of facilities set up with the same ingredients needed for SIFCON. On two recent SIFCON paving projects, standard transit mix concrete trucks were successfully used to mix and transport the slurry to the job site. The trucks were loaded at the concrete batch plant and driven to the job site. At the site, the slurry was discharged in the usual manner onto a fiber bed.

For both projects, the slurry was well mixed and did not contain significant lumps of cement or fly ash. However, it was determined that it was quite difficult to control the discharge of the slurry down the chute. The rapid slurry discharge from the chutes also tended to displace the fibers at the surface of the fiber bed. It was recommended at the time that, if transit mix trucks were to be used in the future, the slurry be discharged into a grout pump and hose system for delivery to the fiber bed.

3.5 SURFACE FINISHING

Finishing SIFCON can be quite difficult, especially if the fibers project above the level of the finished surface. In addition, the high cement content and lack of coarser sands in the slurry generally makes for a sticky surface when finishing with conventional steel trowels. If appearance is a consideration, some sort of finishing layer is usually required. This layer can be applied during the slurry installation or after the SIFCON has cured. Brief descriptions of several finishing layers considered for SIFCON follow.

3.5.1 Seeded Aggregate

For this method the fibers are placed so that the top of the fiber bed is approximately 0.25 in below the level of the finished surface. The slurry is placed to the top of the form so that the fibers are submerged. An aggregate mixture is then broadcast over the surface of the slurry in much the same manner as conventional concrete is seeded for an exposed aggregate finish. Enough aggregate is added to the slurry until a cement-rich "concrete" is formed and the level of the surface is at the desired location. The surface is then finished in a conventional manner and has a conventional concrete appearance.

The aggregate should be graded to produce a workable mixture when combined with the slurry. The maximum size of the aggregate should be small enough not to protrude above the finished surface and also be able to be worked in among the fibers in the top of the fiber bed. Sand should be included in the aggregate mixture to aid in achieving a durable, dense surface, and help in the finishing process. The exact aggregate mixture should be determined by trial batch procedures using the design slurry mix and fiber type.

3.5.2 Preplaced Aggregate

This method utilizes aggregate preplaced in the top surface of the fiber bed during the placing of the fibers. The ratio of aggregate to fiber varies in the top 1 in of the fiber bed from 0 to 100 percent at the top surface (Fig. 14). By placing the aggregate at the same time as the fiber, benefit of the fiber interlocking phenomenon is maintained up to the surface. Once the fiber and aggregate are in place, the slurry is infiltrated into the fiber bed and the preplaced aggregate. The slurry infiltrated aggregate produces a rich "concrete" which is finished using conventional techniques.

The advantage of this system is that the finishing can begin immediately after placing the slurry without the additional step of seeding the aggregate. One disadvantage is that it may be difficult for the slurry to infiltrate into the fiber bed through the preplaced aggregate surface unless the density of the aggregate is reasonably low or the slurry is designed to have a low viscosity. Another disadvantage is that the aggregate should all be uniform in size and not contain any small particles or sand. A well-graded aggregate mixture will almost certainly hinder the infiltration of the slurry and the small-grained particles will fall through the fiber bed. The absence of the sand will result in a sticky surface that is difficult to trowel. However, the lack of sand in the preplaced aggregate topping can be compensated for by including a suitable amount of sand in the slurry.

The use of this method is probably most useful when the slurry is being infiltrated upward through the fiber bed. If the slurry is not adequately infiltrating the upper aggregate surface, some additional slurry may be added from the top.

3.5.3 Fiber Concrete

For this method, the fibers are placed to within 0.5 to 0.75 in of the top of the form (Fig. 15). The slurry is infiltrated through the fibers so that it just slightly covers some of the top fibers in the bed. Next, a conventional Steel Fiber Reinforced Concrete (SFRC) is immediately placed on top of the fiber bed up to the top of the form. This SFRC layer is then worked into the fibers and

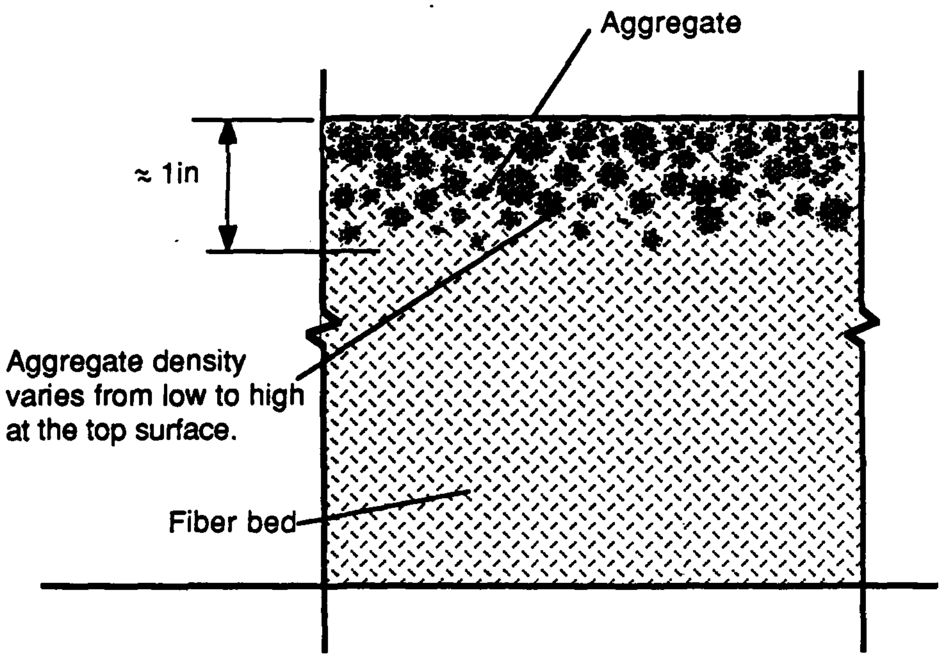


Figure 14. Preplaced aggregate as a finishing layer for SIFCON.

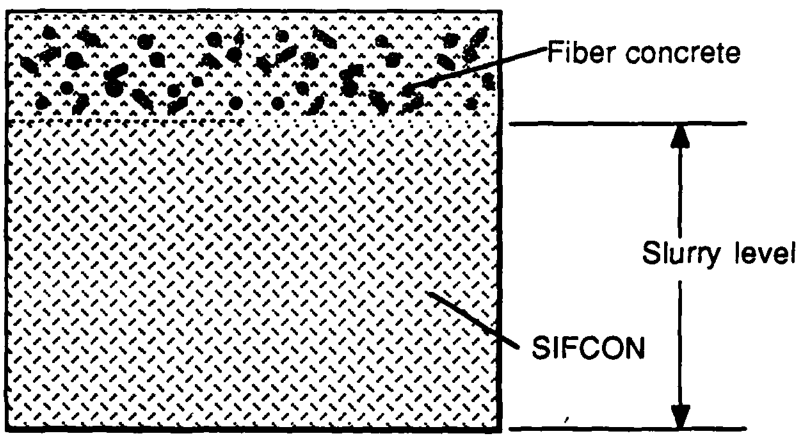


Figure 15. Fiber concrete as a finishing layer for SIFCON.

slurry of the SIFCON layer below and finished in a conventional manner. The steel fibers from the SIFCON layer penetrate the SFRC layer and help to ensure adequate bonding of the two layers. The steel fibers in the SFRC help to control cracking from shrinkage in the surface layer.The advantage of this method is that the design procedures and finishing techniques for SFRC are generally well known today. A disadvantage is that the method uses two materials requiring totally different mixing and placing procedures.

3.6 CURING

The curing procedures for SIFCON are the same as for conventional concrete. Depending on the application, water spray or fogging, wet burlap, waterproof paper, plastic sheeting or liquid membrane compounds can be used. Probably the most practical and economical are the liquid membrane compounds. They are well developed and in common use throughout the concrete industry.

3.7 MAINTENANCE

Because of the relative newness of SIFCON, little is known about the long-term effects of weather on the material. There is some evidence that tends to indicate that SIFCON is highly resistant to deterioration from the weather. A 1987 masters degree thesis research project (Ref. 12) reported that SIFCON was about 100 times more resistant to chloride penetration into a highway bridge deck than a typical latex modified concrete. In 1984, NMERI installed six SIFCON test panels into several bridge decks on the New Mexico Interstate Highway system (Ref. 10). To date, they are still intact with no indication of salt damage or abrasion.

3.7.1 Vertical Surfaces

For a formed vertical surface exposed to the elements such as a wall or a column, some staining and rusting of those fibers exposed on the surface is to be expected. A coating of standard concrete sealer should be applied to the exterior surface to minimize the rusting and streaking.

3.7.2 Horizontal Surfaces

For horizontal surfaces exposed to the elements, an aggregate topping should be used to cover the fibers near the surface. In addition, an application of a standard penetrating concrete sealer should

be used. If the surface is expected to be exposed to a harsh environment, including some chemical solutions, a special slurry mix incorporating latex modifiers should be considered. Consideration should also be given to using a recently introduced epoxy-coated fiber in the upper surface of the fiber bed.

3.8 SUMMARY

The techniques and equipment for efficiently fabricating large SIFCON systems exist today. Some modification of existing equipment to meet specific requirements may be needed, but no new basic equipment or procedures need to be developed. The decision for selecting equipment and techniques for a particular application is based on the combination of many variables such as the characteristics of the fiber, fluidity and open time of the slurry, form geometry, etc. The criteria for making the decision will be fully developed in Phase II of the program described at the beginning of this report. A proposed plan for this Phase is presented later in Section 5.

As noted, SIFCON does not require crews of highly skilled workmen. Semiskilled and unskilled laborers working under a trained supervisor can accomplish virtually all the tasks needed. However, as in all new construction processes, some minimal training for the workforce is naturally recommended.

4.0 SIFCON COSTS

4.1 INTRODUCTION

At first glance SIFCON may appear to be too expensive to be used as a practical building material--but in certain applications SIFCON can be demonstrated to be more economical than conventional materials.

It is important to note that SIFCON material costs should not be compared on a one-to-one basis with the material costs of conventional concretes since it would appear that SIFCON is prohibitively expensive. A total system or structure comparison needs to be considered. In applications where SIFCON would be practical, often the size of the main structural elements can be significantly reduced or other subsystems modified, resulting in the entire system being less costly than those using conventional materials. The costs associated with construction techniques, maintenance, and structure life must also be included for a fair comparison. When such a combined comparison of the entire system is considered, the cost of SIFCON is often found to be more economical than conventional concrete.

An attempt was made in this program to identify and establish the costs of using SIFCON in practical applications. These cost estimates include not only the material costs, but costs of SIFCON placement. For a given SIFCON mix, the material costs were quite easy to identify, since they are related to the basic unit costs of the ingredients. However, the costs of SIFCON placement were found to vary greatly since there are many more variables involved in determining these costs.

4.2 MATERIAL COSTS

The material costs of SIFCON are dependent on the actual mix ingredients used and their unit costs. The unit costs used for the purpose of this study were obtained from competitive commercial sources, and reflect 1987 local or national industry unit prices for orders of moderate size. For larger orders, the prices could be expected to be less. High-strength SIFCON, in general, will cost more than lower-strength SIFCON. For the purpose of this study, mixes of known parameters and strengths developed in Reference 3 were used. These mixes represent relatively high-strength SIFCON slurries. Therefore, overall, the costs presented in this study should be considered as an upper limit.

Table 1 presents detailed costs for three selected SIFCON slurry mixes. These mixes could potentially be used in large-scale field applications. The specific mix proportions are presented in Table 2.

The individual tables for each mix have two parts. The upper portion of the table presents the cost for the specific mix that was actually made. The bottom portion shows the costs for a designed mix without the sand and aggregate, but retaining the same mix proportions for the rest of the ingredients. Both portions present the costs per cubic yard of each individual ingredient and a total summation of these costs. The top portion of each table also presents the actual average ultimate strength results for each specific slurry and SIFCON. From the ultimate strength results and the total cost values, a strength-to-cost ratio can be calculated. This strength/dollar factor gives a relative indication of the cost efficiency of the different SIFCON fibers.

The tables show that the largest percentages of the SIFCON costs are found in the cost of the fibers (approximately 70-85 percent). SIFCON mixes with higher percentages of fibers are more expensive. However, for the fiber types tested there was a tendency of higher SIFCON strengths for mixes with higher fiber percentages. The range of costs for these three SIFCON groups was \$846 for SIFCON with 11 percent of ZL 30/50 fibers, to \$487 for SIFCON with 6 percent of ZL 60/80 fibers with aggregate interspersed. The strength/ dollar factor varied from mix to mix. Within each mix, this factor was highest for the ZL 50/50 fiber and the ZL 60/80 fiber with aggregate interspersed.

As shown in the tables, significant savings can be gained by the use of sands and aggregates. The tables compare the percent savings realized with the use of the sand and/or aggregate compared to the same mix with the sand and aggregate omitted. The percent savings is calculated by subtracting the total cost of the mixes containing the sand and/or aggregate from the cost of mixes without them and then dividing by the cost of the mix without sand and/or aggregate. The savings are greatest when sand and aggregate are both used. Using a high percentage of sand and some aggregate, the savings are about 30 percent. Even with a low percentage of sand and some aggregate, the savings are 26 percent. Using sand without aggregate results in cost savings between 6-11 percent. Sand reduces costs because it replaces more expensive slurry ingredients such as cement. Using a small quantity of aggregate significantly reduces costs because it not only replaces the more expensive slurry ingredients but it also reduces the percentage of the fiber. This reduction in fiber percent also accounts for the reduction in strength when comparing the strengths of the SIFCON with the aggregate to the same SIFCON without aggregate.

TABLE 1. SIFCON material costs.

Unit costs

Material	Units	Cost
Cement	$/lb	0.0530
Fly ash	$/lb	0.0225
Sand	$/lb	0.0100
Aggregate	$/lb	0.0060
Microsilica (EMS 960)	$/lb	0.0800
Superplasticizer	$/gal	7.5000
Fiber	$/lb	0.4800

Efficiency factor =

$$\frac{(SIF - Slu)/Slu}{Fib}$$

Where : SIF = SIFCON strength
Slu = Slurry strength
Fib = Steel fiber percent

Mix 1, high strength, with sand/cement=150%, and microsilica

Material	Material costs, $/yd^3				
	Slurry	ZL30/50 11%	ZL50/50 6%	ZL60/80 8.50%	Agg. & ZL60/80 6.06%
Cement	64.52	57.43	60.65	59.04	52.28
Sand	18.26	16.25	17.17	16.71	14.80
Aggregate					3.39
Microsilica (EMS 960)	14.57	12.97	13.70	13.33	11.81
Superplasticizer	36.09	32.12	33.93	33.02	29.24
Fiber		698.54	381.02	539.78	384.83
Total cost, $	133.45	817.31	506.46	661.89	496.36
Strength, lb/in^2	11,209	25,724	17,851	18,448	16,968
Strength/Dollar, lb/in^2/$	84	31	35	28	34
Efficiency factor		11.8	9.9	7.6	8.5
Same mix omitting the sand and aggregate					
Cement	110.66	98.48	104.02	101.25	101.25
Microsilica (EMS 960)	24.99	22.24	23.49	22.86	22.86
Superplasticizer	61.89	55.09	58.18	56.63	56.63
Fiber	0.00	698.54	381.02	539.78	539.78
Total cost, $	197.54	874.35	566.71	720.53	720.53
Savings, %	32.44	6.52	10.63	8.14	31.11

TABLE 1. Concluded.

Mix 2, Moderately high strength, with sand/cement-150%

Material	Material costs, \$/yd³				
	Slurry	ZL30/50 11%	ZL50/50 6%	ZL60/80 8.50%	Agg. & ZL60/80 6.06%
Cement	65.89	58.64	61.93	60.29	53.74
Fly ash	3.11	2.77	2.92	2.84	2.54
Sand	18.65	16.60	17.53	17.06	15.21
Aggregate					3.25
Superplasticizer	32.41	28.84	30.46	29.65	26.43
Fiber		698.54	381.02	539.78	386.10
Total cost, \$	120.05	805.39	493.87	649.63	487.27
Strength, lb/in²	7,220	19,033	13,076	14,070	12,783
Strength/Dollar, lb/in²/\$	60	24	26	22	26
Efficiency factor		14.9	13.5	11.2	12.7
Same mix omitting the sand and aggregate					
Cement	114.73	102.11	107.84	104.97	104.97
Fly ash	5.41	4.82	5.09	4.95	4.95
Superplasticizer	56.43	50.22	53.04	51.63	51.63
Fiber	0.00	698.54	381.02	539.78	539.78
Total cost, \$	176.56	855.69	546.99	701.34	701.34
Savings, %	32.01	5.88	9.71	7.37	30.52

Mix 3, Moderately high strength, with sand/cement-50%, and microsilica

Cement	88.12	78.43	82.83	80.63	70.62
Fly ash	4.16	3.70	3.91	3.80	3.33
Sand	8.31	7.40	7.81	7.61	6.66
Aggregate					3.58
Microsilica (F 10,000)	19.95	17.76	18.75	18.26	15.99
Superplasticizer	44.90	39.96	42.21	41.09	35.99
Fiber		698.54	381.02	539.78	395.63
Total cost, \$	165.44	845.79	536.54	691.17	531.80
Strength, lb/in²	10,661	18,889	15,000	15,453	14,925
Strength/Dollar, lb/in²/\$	64	22	28	22	28
Efficiency factor		7.0	6.8	5.3	6.4
Same mix omitting the sand and aggregate					
Cement	108.76	96.80	102.23	99.51	99.51
Fly ash	5.13	4.57	4.82	4.69	4.69
Microsilica (F 10,000)	24.62	21.92	23.15	22.53	22.53
Superplasticizer	55.42	49.32	52.10	50.71	50.71
Fiber	0.00	698.54	381.02	539.78	539.78
Total cost, \$	193.94	871.15	563.32	717.23	717.23
Savings, %	14.69	2.91	4.75	3.63	25.85

TABLE 2. Selected SIFCON mix proportions.

Constants:	Fiber types:	Dramix ZL 30/50, ZL 50/50, ZL 60/80
	Sand type:	50-mesh sand
	Aggregate:	3/4-in concrete aggregate
Variables:	Sand/cement:	50 and 150 percent
	Water/cement + fly ash:	0.35 to 0.4233
	Microsilica:	0 to 15 percent
	Superplasticizer:	36.55 to 44.01 oz/100 wt

Mix proportions:

Mix identification code	Cement (C/C+FA), %	Fly ash (FA/C+FA), %	Water (W/C+FA)	Microsilica (M/C), %	Superplasticizer, oz/100wt	Sand (S/C), %	Aggregate (A/C), %	Fiber, %by vol.
Mix 1	100	0	0.4233	14.96	44.01	150	0.00	11, 8.5, 6
Aggr. & ZL 60/80	100	0	0.4233	14.96	44.01	150	57.34	6.06
Mix 2	90	10	0.3713	0.00	40.04	150	0.00	11, 8.5, 6
Aggr. & ZL 60/80	90	10	0.3713	0.00	40.04	150	53.35	6.08
Mix 3	90	10	0.3500	15.00	36.55	50	0.00	11, 8.5, 6
Aggr. & ZL 60/80	90	10	0.3500	15.00	36.55	50	44.81	6.23

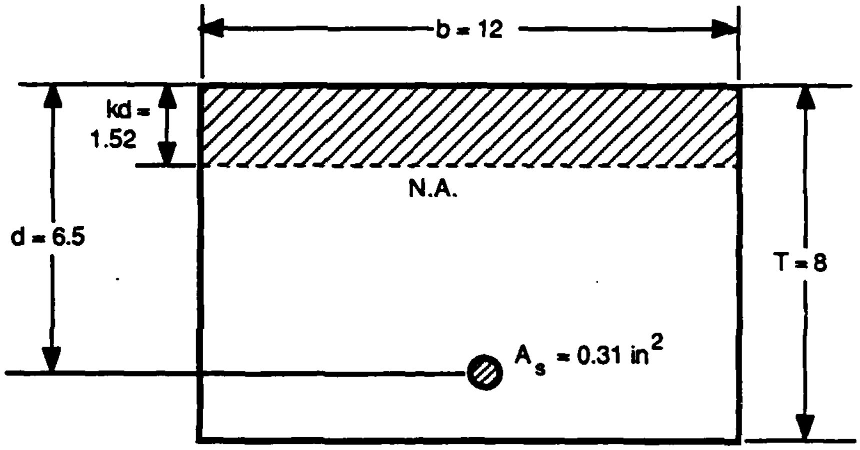
4.3 ALTERNATE DESIGNS WITH SIFCON

In support of the SIFCON cost study, a series of structural designs were made using both reinforced concrete and SIFCON. Calculations were made using elastic principles to determine the section properties and allowable bending moment of each design. These designs were then compared to determine if there were any advantages of one design over the other.

The first study presented is a typical flexural element, such as a slab. This is followed by a study on a recently constructed bridge deck slab.

4.3.1 Slab Flexure Design

The baseline reinforced concrete system is shown in Figure 16. Using basic elastic principles, the moment of inertia of the section was calculated to be 83.24 in^4. Then using typical allowable design stresses for the concrete and reinforcing steel, the bending moment capacity of the section was calculated to be 44.6 in-k.



Note : Dimensions in inches unless otherwise specified.

f'_c = 4,000 lb/in^2, allowable concrete compressive stress =1,800 lb/in^2

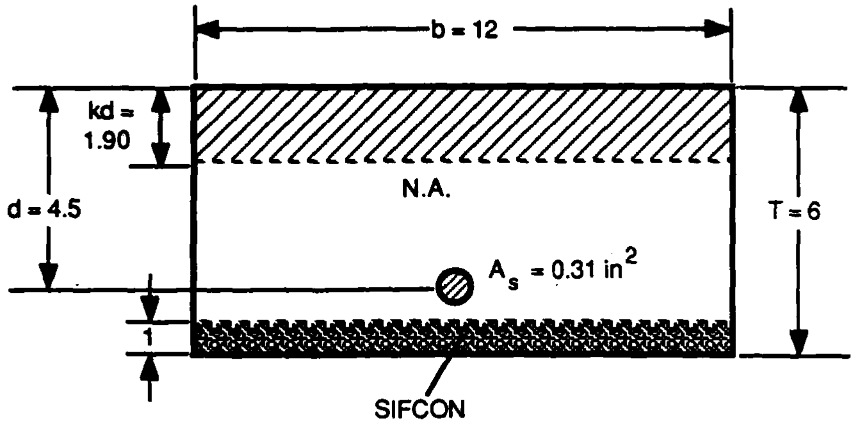
F_y = 60,000 lb/in^2, allowable reinforcement tensile stress = 24,000 lb/in^2

E_{steel} = 29,000,000 lb/in^2

Figure 16. Baseline conventional concrete slab design.

The baseline section was then reduced to a thickness of 6 in, including 1 in of SIFCON added on the tension side (Fig. 17). The same reinforcing used for the baseline section was also used. Assuming the SIFCON remained uncracked, and transforming the SIFCON and reinforcing to equivalent areas of concrete, the moment of inertia for the section was calculated to be 98.47 in^4. This was 18 percent larger than the baseline section, despite a 25-percent reduction in the depth of the member. To calculate the bending capacity of the section, an allowable tensile stress for the SIFCON of 1000 lb/in^2 was used. This value was 20 to 30 percent of typical modulus of rupture values for SIFCON flexure test specimens (Ref. 2). Using this value, and the allowable values for the concrete and reinforcing, the bending capacity of the section was calculated to be 72.7 in-k. This was 63 percent greater than the capacity of the baseline section.

The second section was then further reduced to a thickness of 5 in, including 1 in of SIFCON on the tension side and the same reinforcing as the baseline (Fig. 18). The moment of inertia for this third section was calculated to be 60.33 in^4, or 27 percent smaller than the moment of inertia of the baseline section. The bending moment capacity for the section was calculated to be 64.4 in-k, or 44 percent greater than the capacity for the baseline section.

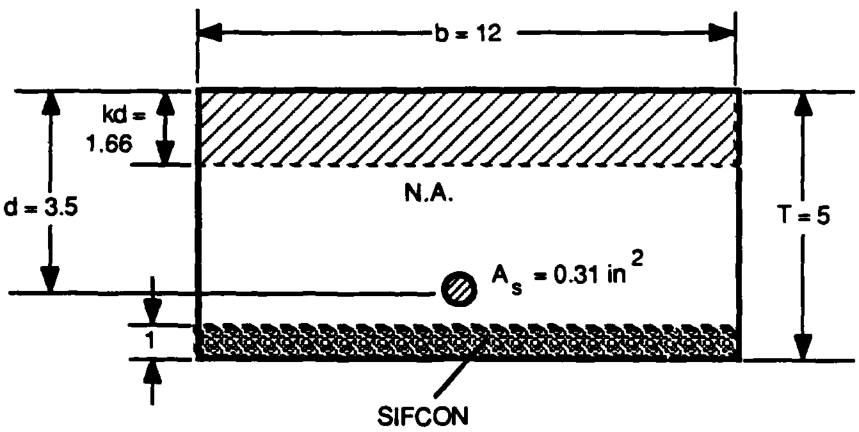


Note : Dimensions in inches unless otherwise specified.

f'_{SIF} = 15,000 lb/in^2, allowable SIFCON tensile stress = 1,000 lb/in^2

E_{SIF} = 1,000,000 lb/in^2

Figure 17. Section used for second example.



Note : Dimensions in inches unless otherwise specified.

Figure 18. Section used for third example.

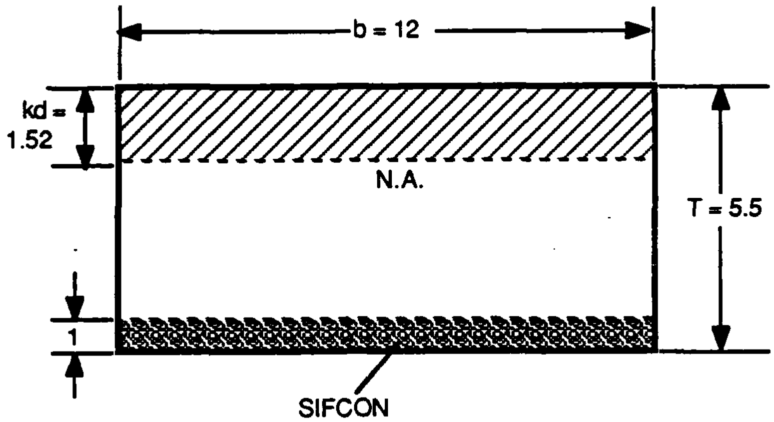
For the fourth section, the thickness was chosen to be 5.5 in, including 1 in of SIFCON on the tension side, and the reinforcing steel used in the first three sections was eliminated (Fig. 19). The moment of inertia of this section was calculated to be 62.82 in^4, or 75 percent less than the moment of inertia of the baseline section or about the same as the second section. The bending moment capacity was calculated to be 47.8 in-k or nearly the same as the bending capacity of the original baseline section.

Table 3 summarizes the calculations of all four sections and includes a cost index. The index is determined by using a value of 1 per inch thickness of concrete, and a value of 2.5 per inch thickness of SIFCON as taken from the costs developed later in this section. For this study, the cost of the reinforcing bar was assumed to be relatively small in comparison and was not considered in determining the index. This assumption affects only the fourth section, where the actual index would be slightly smaller than that indicated.

As shown in Table 3, example 2, reducing the thickness of the baseline section 25 percent from 8 in to 6 in, and including only 1 in of SIFCON resulted in a section of greater stiffness, higher bending moment capacity and a smaller cost. A 37-percent reduction in the thickness to 5 in, example 3, and including 1 in of SIFCON resulted in a section having a lower stiffness than the baseline section but still having a higher bending moment capacity. In addition, the cost index was 18 percent less than for the baseline section.

Table 3 also shows that a section (Example 4) was designed having a similar bending moment capacity as for the baseline section but having a 30 percent smaller thickness and no reinforcing other than SIFCON. In addition, the cost index of the section was 12 percent less than that for the baseline section.

In summary, these calculations show that flexure members can be designed using SIFCON which have equal or higher stiffnesses and bending moment capacities than those of deeper reinforced concrete flexure members. In addition, the members using SIFCON are generally more economical than the deeper concrete members.



Note : Dimensions in inches unless otherwise specified.

Figure 19. Section used for fourth example.

TABLE 3. Design calculation summary.

	Baseline design concrete	SIFCON design, examples		
	1	2	3	4
Thickness (in)	8.00	6.00	5.00	5.50
Reinforcement (in^2)	0.31	0.31	0.31	0.00
SIFCON thickness (in)	0.00	1.00	1.00	1.00
Moment of inertia (in^4)	83.24	98.47	60.33	62.82
Allowable bending moment (in-k)	44.60	72.70	64.40	47.80
Cost index	8.00	7.50	6.50	7.00

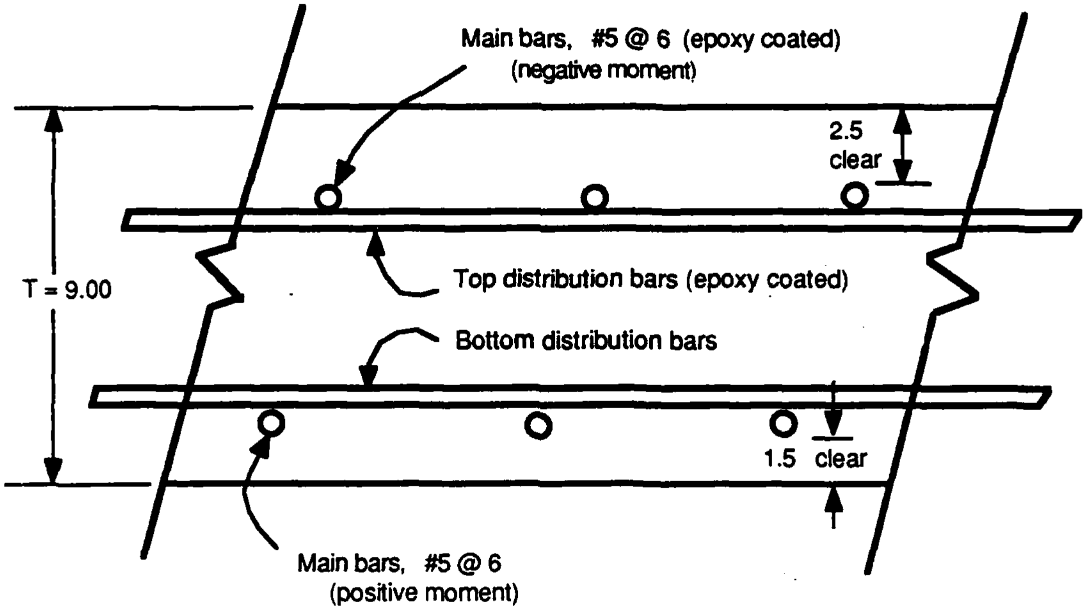
4.3.2 Bridge Deck Design

As a practical illustration of the principles discussed above, a typical reinforced concrete bridge deck was redesigned using SIFCON. The bridge had been completed several months earlier and had been designed using the American Association of State Highway and Transportation Officials (AASHTO), and the New Mexico State Highway Department (NMSHD) standard specifications for highway bridges. A cross section of the deck is shown in Figure 20. It was 9 in thick and the main tensile reinforcing was No. 5 deformed reinforcing bars at 6-in spacing. The deck was designed as a continuous member supported by prestressed concrete beams. The critical section for design was located at the supports, putting the top reinforcing in tension. Of interest is the 2.5 in of clear cover used over the top bars, and the fact that the top reinforcing bars are coated with epoxy. The large amount of clear cover and the epoxy coating are attempts by the highway department to protect the reinforcing from the deicing chemicals used on the bridges. Similar methods of protection are used throughout most of the United States and Europe.

The dead load of the slab was calculated to be 112.5 lb/ft^2. Adding a specified future load of 30 lb/ft^2 to the deck dead load, and using equations from the AASHTO standards, the dead load moment was calculated to be 12.6 in-k/ft width of slab. Also using equations from the AASHTO standard, the live load bending moment was calculated to be 66.0 in-k/ft width, for a total service load moment of 78.6 in-k/ft width. The factored load, or "ultimate load," bending moment was calculated to be 159 in-k/ft width.

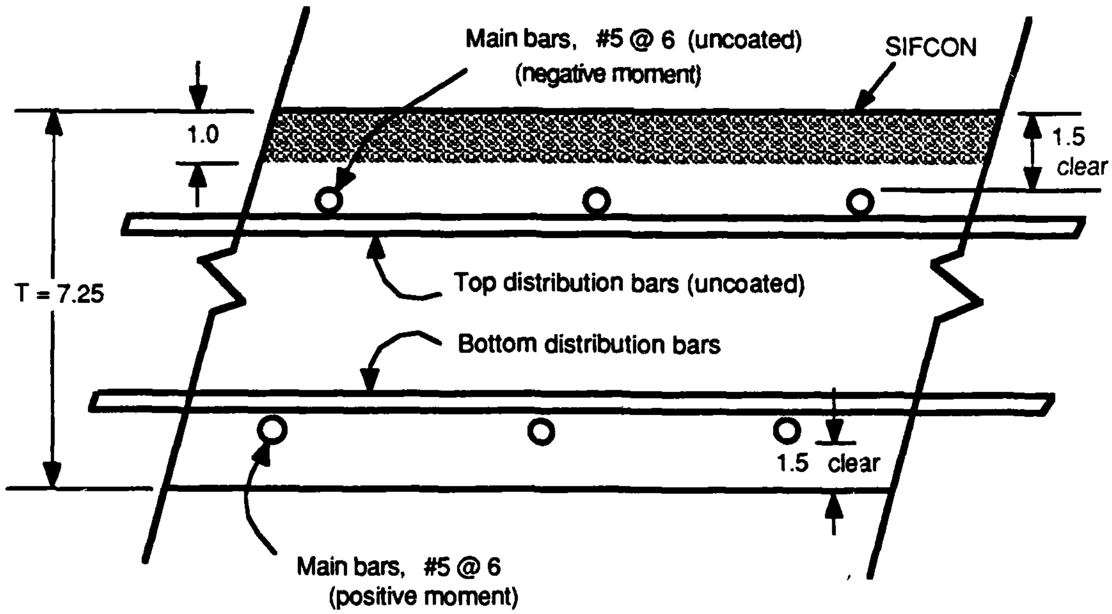
Using elastic principles, the moment of inertia of the section was calculated at 129.83 in^4/ft width. The maximum stresses in the concrete and reinforcing steel resulting from the service load were calculated to be 1200 lb/in^2 and 22,900 lb/in^2 respectively. The bending moment capacity of the member was calculated to be 170.0 in-k/ft width.

The section was then redesigned with a thickness of 7.25 in, including 1 in of SIFCON on the top, or tension side, of the member (Fig. 21). In addition, the 2.5 in of clear cover was reduced to 1.5 in. This reduction in the cover was done because of the apparently high resistance to cracking and chloride intrusion of SIFCON (Ref. 12). Because of the reduction in thickness, the dead load of the slab was reduced to 90.625 lb/ft^2. The dead-load moment, including the specified future load, was recalculated to be 11.0 in-k/ft width. The live-load moment remained the same at 66.0 in-k/ft width, for a total service load moment of 77 in-k/ft width. The factored-load bending moment was calculated to be 157.0 in-k/ft width.



Note : Dimensions in inches.

Figure 20. Section of bridge deck slab.



Note : Dimensions in inches.

Figure 21. Redesigned bridge deck section with SIFCON.

The moment of inertia for the redesigned section was calculated to be 182.80 in^4/ft width. The maximum stresses were calculated to be 1000 lb/in^2 for the concrete, 11,500 lb/in^2 for the steel reinforcing and 600 lb/in^2 for the SIFCON. The bending moment capacity of the member was calculated, assuming the SIFCON to be ineffective, to be 161 in-k/ft width.

As a point of interest, the stresses in the 7.25-in-thick section were recalculated assuming the SIFCON to be ineffective. The stress in the concrete was 1450 lb/in^2 and the stress in the reinforcing was 25,600 lb/in^2. Both of these values were found to be above the allowable values specified in the standards, indicating that without SIFCON the section would not be acceptable.

Table 4 summarizes the section properties, stresses and capacities of the two sections. In addition, a cost index was calculated for both sections using the same values as for the slab design examples presented earlier. As indicated in the table, the design with SIFCON resulted in a section that was 19 percent lighter and 40 percent stiffer than the original deck design. The stress in the reinforcing bars of the section using SIFCON were 50 percent smaller than for the conventional design.

The cost index for both the sections were about the same, with the index for the section using SIFCON being slightly smaller. The redesigned section also includes additional cost-saving characteristics not considered by the cost index. These include having an abrasion-resistant surface which is about 100 times more resistant to chloride penetration than a typical latex-modified concrete deck (Ref. 12). In addition, because of SIFCON's characteristic ability to resist cracking and its high resistance to chloride penetration, the epoxy coating on the top reinforcing bars can be eliminated. The wear resistant surface will require less maintance in the future and prolong the overall life of the deck. The reduction in the dead load of the deck will also affect the final design of the beams and substructure, resulting in additional cost savings.

4.4 FABRICATION COSTS

As noted earlier, the fabrication costs associated with SIFCON are not as easily defined as the material costs since there are many more variables involved. There also is an absence of actual large-scale SIFCON construction experience to draw on. The cost estimates presented in this report are preliminary estimates, and are considered conservative cost estimates that can be reduced by efficiency and innovation in actual practice.

TABLE 4. Redesigned bridge deck calculation summary.

	Original design	SIFCON design
Thickness (in)	9.0	7.25
d (in)	6.1875	5.4375
Reinforcement	#5@6" (Epoxy)	#5@6"
SIFCON thickness (in)	0.0	1.0
D.L. weight (lb/in^3)	112.5	90.625
Ultimate moment from load (in-k)	159.0	157.0
Moment capacity (in-k)	187.0	161.0
Moment of inertia (in^4)	129.83	182.80
Concrete stress (lb/in^2)	1,197	1,003
Steel reinforcement stress (lb/in^2)	22,935	11,508
SIFCON stress tension (lb/in^2)	--	604
Cost index	9.00	8.75

Some variables associated with SIFCON construction that make it difficult to set firm construction costs are similar to those of conventional concretes. First, each SIFCON application must be estimated individually. The cost of fabricating a conventional reinforced concrete floor deck is much different than the cost of constructing a conventional reinforced concrete floor slab on grade of equal dimensions. Different SIFCON applications will also vary greatly in costs. Second, to date, only small-scale SIFCON projects have been constructed and production-efficient methods have not been developed. Third, there has been only limited experience using the available equipment that would permit easy and rapid SIFCON placement.

4.4.1 Determination of Construction Cost Index

Using the material costs and design data just discussed, cost comparisons were made between the conventional bridge deck design and the SIFCON composite design (Fig. 22). The results of this cost comparison are contained in Table 5. The costs of the conventional design are the actual contract costs of the low bid contractor for the Paseo Del Norte bridge project, and represent actual New Mexico State Highway Department (NMSHD) 1986-87 costs for bridge construction. The

TABLE 5. Conventional versus SIFCON cost comparison.

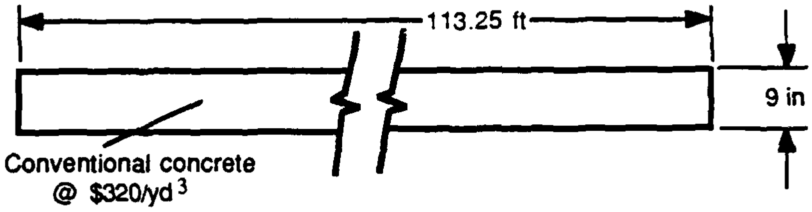
Item no.	Bridge items	Unit	Conventional design			SIFCON design		
			Engineer's estimate	Contractor's bid		NMERI estimate		
				Unit cost	Total cost	Estimate	Unit cost	Total cost
	Bridge deck :							
504015	Reinforcing bars grade 60	lb	701,680	0.35	245,588	1,029,082	0.35	360,179
504019	Epoxy-coated reinforcing bars grade 60	lb	545,670	0.40	218,268	218,268	0.40	87,307
509080	Superstructure concrete class A	yd^3	5,155.8	320.00	1,649,856	3,498	406.00	1,420,107
-	Superstructure deck SIFCON	yd^3	-	-	-	311	882.00	274,567
					2,113,712			2,142,159

SIFCON cost index
(concrete = 1.0)

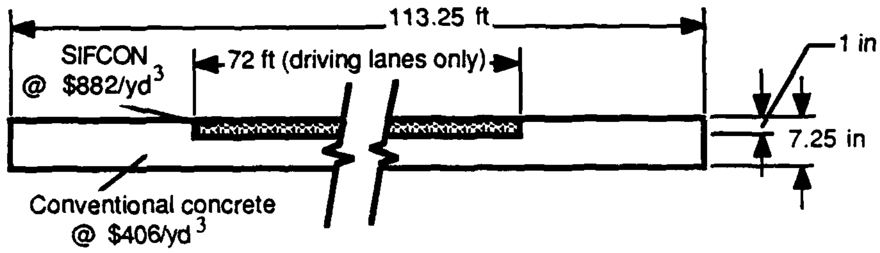
(separate systems) $\dfrac{\text{SIFCON}}{\text{concrete}}$ $\dfrac{882}{320} = 2.75$

(hybrid system) $\dfrac{\text{SIFCON}}{\text{concrete}}$ $\dfrac{882}{406} = 2.17$

Average = 2.46 Use 2.5



(a) Conventional concrete bridge deck section.



(b) SIFCON composite bridge deck section.

Figure 22. Conventional concrete versus SIFCON composite designs.

SIFCON alternate design costs are conservative estimates. The costs of the conventional items are based in part on the contractor's bid costs and also on cost factors contained in the 1986 Dodge estimating handbook (Ref. 13). Costs of the SIFCON items are also based on the material costs discussed earlier in this section for ZL 50/50 fibers and on labor and equipment estimates derived from limited experience. The only costs that are a little uncertain, and therefore kept conservative, are those associated with SIFCON.

The total costs of the two designs are within 2 percent of each other, showing that when an entire system is considered, the costs of using SIFCON are competitive even though the material costs of SIFCON are high.

4.5 SUMMARY

This cost study clearly demonstrates the practicality and feasibility of using SIFCON in large-scale applications. The results demonstrate that when an entire structure design is considered, SIFCON costs are competitive with conventional concretes. The use of SIFCON then affords attractive advantages over conventional materials.

5.0 CONCLUSIONS AND RECOMMENDATIONS

5.1 DEVELOPMENT OF DESIGN METHODS

Although there is still much work to be done, the knowledge and data base for SIFCON material properties is rapidly expanding from work being done at NMERI and by a growing number of researchers around the country. If this information is to be utilized to develop structural design methods for SIFCON, a comprehensive testing program will be required to verify the procedures. This would follow a process similar to that used to develop the methods used today for conventional reinforced concrete. Such a program should include the fabrication and testing of full-size or subscale models of structural elements which were designed using the proposed methods. Based on the test results, the design methods would be refined as needed to accurately model the observed response. The program will require careful planning, adequate funding and continuing evaluation; but if the full potential of SIFCON as a structural material (as briefly illustrated in the report) is to be developed, the program must be pursued.

5.2 CONSTRUCTION TECHNIQUES

To evaluate and verify the construction procedures discussed in Section 3.0, a variety of structural elements should be fabricated using the techniques outlined. These elements can then be tested to provide a basis for revising the proposed construction procedures as well as developing methods for design. To meet these objectives, it is recommended that a simple structure as shown in Figure 23 be fabricated and tested. This particular system includes all the structural elements normally associated with conventional construction.

5.2.1 Floor Slab

This element will provide a means to evaluate the techniques needed to fabricate SIFCON on grade. Following are a few of the techniques which can be developed and evaluated using this element:

- Rapidly placing fiber to a uniform thickness over the slab area
- Sealing the subgrade to prevent leakage of the slurry
- Placing slurry into a shallow fiber bed
- Finishing flatwork
- Achieving an interface between conventional concrete and SIFCON topping aggregates
- Curing

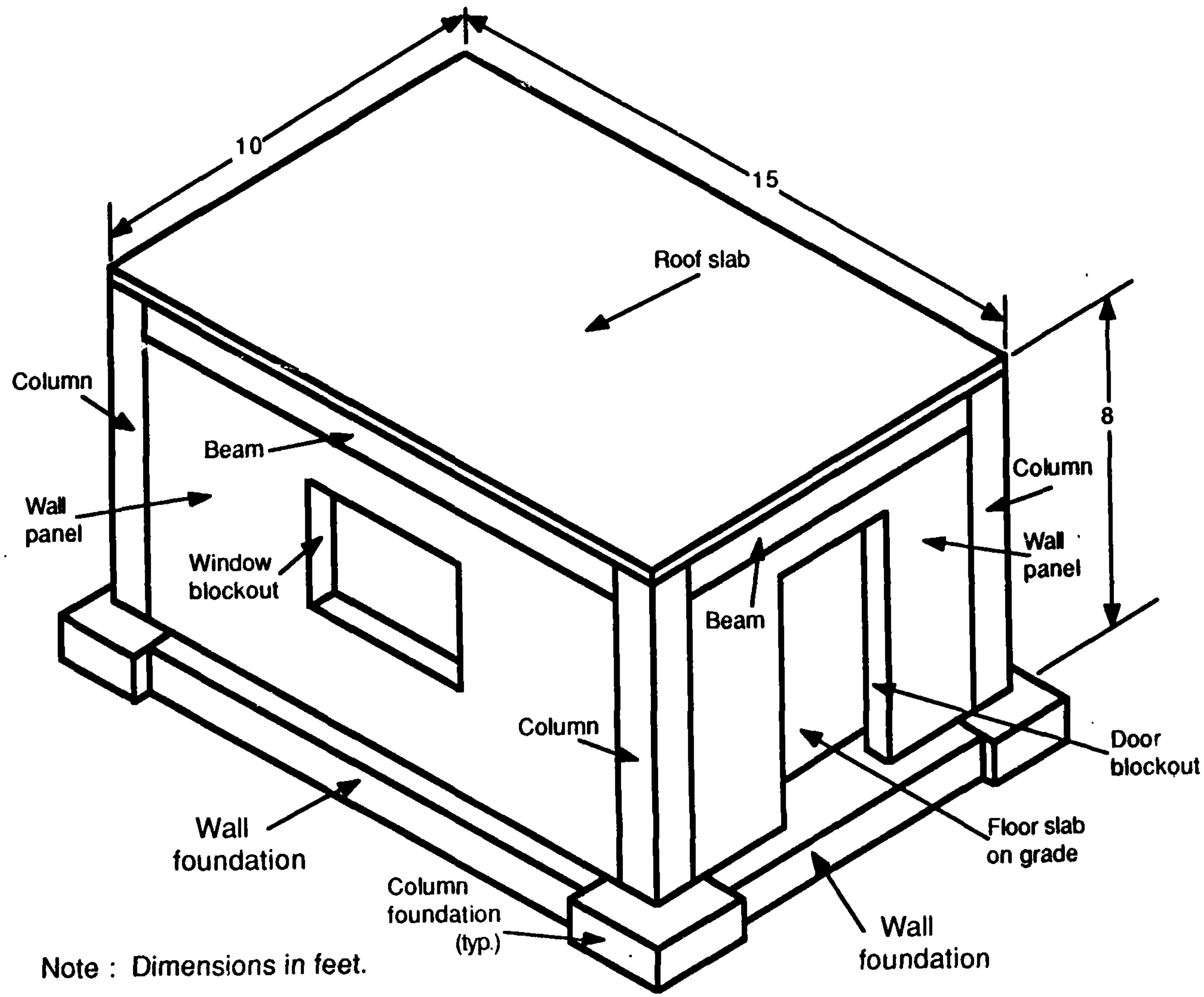


Figure 23. System for evaluation of SIFCON construction techniques.

5.2.2 Columns

These elements will provide a means to evaluate the fabrication of vertical SIFCON elements to resist compression and bending loads. In addition, each of the four columns can be fabricated with a different fiber or slurry mix. The following techniques can be studied:

- Formwork design and fabrication for high pressures
- Pumping slurry from the bottom
- Pouring slurry from the top
- Placing fibers in narrow formwork
- Hybrid systems combining conventional reinforcing bars and SIFCON

5.2.3 Beams

These elements will provide a means to evaluate forming and fabricating horizontal SIFCON flexural members. Each of the four beams can be fabricated with different fiber types or slurry mixes. The following techniques can be studied:

- Formwork design for low pressures
- Fiber placement in long and narrow forms
- Hybrid systems with SIFCON and conventional reinforcing
- Hybrid systems with SIFCON and conventional concrete
- Slurry placement in forms of moderate depth

5.2.4 Walls

These elements will provide a means to evaluate forming large volume but narrow elements. Each of the four walls can be fabricated with different fiber types. In addition, the walls can be fabricated in place or precast and installed later. The following techniques can be studied:

- Formwork design and fabrication for high pressures
- Pumping slurry from the bottom
- Pouring slurry from the top
- Placing fiber in formwork with long and narrow dimensions
- Hybrid systems with conventional reinforcing bars

- Precasting
- Surface texturing
- Surface coating and sealing
- Weather effects
- Fabricating blockouts

5.2.5 Roof Slab

This element will provide a means to evaluate the forming and fabrication of an above-grade slab. The following techniques can be evaluated:

- Forming above-grade flatwork
- Rapidly placing fiber to a uniform thickness
- Placing slurry into a shallow fiber bed
- Finishing flatwork
- Curing

5.3 EQUIPMENT

To support the above-described program, some fiber and slurry placing equipment will need to be purchased or fabricated.

5.3.1 Slurry-Placing Equipment

It is recommended that the existing grout mixing equipment at NMERI be utilized for this program. This equipment can be used in combination with mixing and transporting the slurry in transit-mix trucks. However, if funds are available, the purchase of a moderate-sized mobile slurry mix system should be seriously considered. In addition to being used on the upcoming program, the equipment would improve the efficiency and quality of future Air Force SIFCON programs.

5.3.2 Fiber-Placing Equipment

As noted in this report, the hand placement of fiber is probably the least efficient of all the elements of SIFCON fabrication. Unless the fibers can be placed by mechanized methods , SIFCON can not be fabricated efficiently on a conventional scale. Because of its relatively low cost and wide

range of available sizes, it is recommended that a vibrating screen type system be purchased or fabricated as part of a fiber-placing system. In addition, it is recommended that both a small conveyor belt system and a vibrating tray system, compatible with the vibrating screen system, also be purchased.

5.4 COSTS

The results of the SIFCON construction cost study demonstrates that SIFCON can be a cost-effective building material. Even though SIFCON material costs are relatively high, in certain applications these materials can be cost competitive with conventional materials. The use of SIFCON often permits the reduction in size of conventional structural members. The cost competiveness will be realized when the cost of an entire system is taken into consideration.

5.5 CONCLUSION

It is apparent that SIFCON's development has moved out of the laboratory and into functional areas. The current level of knowledge and understanding of SIFCON is such that it can be designed and fabricated into a wide variety of engineered structures with a high level of confidence. This is not to say that everything is known about SIFCON, or that design and fabrication techniques need no further development. Quite the opposite is true. However, the same can be said for conventional reinforced concrete. There has been continual research and development work done on concrete for many years, and it is still going on; but that has not stopped concrete from being used as a common building material within the limits of the knowledge available.

SIFCON's high strength, toughness, and ability to resist penetration by fragments and ballistics make it an ideal material for building new hardened military structures, or for economically upgrading existing facilities. Some applications for SIFCON in the military community can and are being accomplished today. At this point the potential benefits of using SIFCON for military applications appear to be almost limitless, and are constrained only by the current knowledge of the material. However, to benefit from the full potential of SIFCON as a building material, programs, like the type described earlier in this report, need to be undertaken soon. In addition, programs to expand and verify the current knowledge data base of the material should continue as well as expand into new areas such as abrasion or freeze-thaw characteristics.

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